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The ship as whole represents quite a complex noise source. The generated noise affects definitely people on board the vessel (crew and passengers, directly exposed to sound pressure levels) but third parties as well, which may be reached by airborne or underwater noise transmission from the ship: inhabitants of areas near the coastline and near ports, the marine fauna living in zones with intense maritime traffic). The threefold aspect of the acoustical impact of ships (internal to the vessel, external in air and in water) is covered in the paper, which identifies in each context the main sources of noise, the potential receivers and the transmission paths linking sources and receivers. The state of the art and new trends in the characterization of the sources are evaluated, as well as the means available to model the transmission of acoustical power along the various effective paths. The available means for charactering the perception by the receivers in the various contexts are considered, in order to assess the impact of the noise radiation. The more or less recent introduction of norms and requirements in the different fields are discussed and analyzed, in order to highlight the evolution of the societal concern about the ship noise impact on second and third parties of the maritime transportation process. Such concern justifies the undergoing process of further implementations in the normative framework. The trends of this evolution are finally discussed, with description and motivation of pre-normative proposals covering the three aspects above mentioned. The work builds on the results of project SILENV, recently funded by the EU.

1. Introduction

In all vehicles, the presence, on one hand, of powerful noise sources on board, related in particular to propulsion, and the need, on the other hand, for lightweight structures to optimise performances, create the bases for high pressure levels in the spaces inside the vessels, that are also geometrically close to the sources themselves. This represents a common feature for road vehicles, trains, airplanes and ships, marking the difference with the other types of fixed anthropogenic noise sources (industrial plants, buildings, etc.). Another characteristics common to all types of vehicles is related to the fact that, being moving noise sources, the areas where the impact of external noise radiation is effective increase significantly. A peculiarity of ships in respect to external radiation is represented by their moving at the air/water interface and therefore radiate in both media.

The state of the art of the normative frameworks regarding the three contexts identified above (towards internal spaces, outwards in air and outwards in water) will be reviewed in the following, covering the aspects of generation, transmission and perception of noise, of the existing norms and requirements as well as of the trend in the development of new Rules. Finally, a set of pre-normative requirements for sea-going vessels, developed within the SILENV Project funded within the 7th EU Framework Programme, will be introduced.
2. Noise inside ships

Noise control on board ships play today a significant role in the design of pleasure crafts and passenger ships, but also of commercial vessels. Motivations for noise control, values of limit levels and ways of verifying their fulfilment are addressed by a number of international requirements.

From a regulatory point of view, international organizations primarily involved in the control of noise inside the ships are two United Nations’ agencies: the International Labour Organization (ILO) and the International Maritime Organization (IMO). Other requirements have been issued by most Classification Societies (CS) in terms of Comfort Classes (CC), i.e. voluntary class notations assessing the comfort onboard ships. ILO, being the United Nations agency responsible for drawing up and overseeing international labour standards, covers the aspect of noise and vibration for workers on board at a very general level in documents 1,2,3,4 dealing also with a large number of other subjects related to work issues. The background of these documents as concerns noise is not very technical: the texts do not go beyond general motivations and aims, in some cases indicating means to improve the conditions of workers, but never giving precise or quantitative information on how to check the acceptability of conditions on board. In the following, these documents will not be analysed in more details.

As known, the International Maritime Organization (IMO) is a specialized agency of the United Nations dedicated to shipping activities worldwide for what concerns safety, legal matters, environmental concern and efficiency. The most specific document that presently (April 2014) covers extensively and in details the issue of noise control on board commercial ships is still Resolution A.468(XII)5, in the following indicated as ‘Noise Code’ (NC). Noise control requirements are also mentioned in the International Convention for the Safety of Life at Sea6, referring to the NC in its more recent versions. The Code has represented in the last three decades a comprehensive reference for shipping. Even though it was not at a mandatory requirement, most of the National Norms issued in the last three decades referred to it, making the Code a compulsory standard in practice.

IMO started recently an updating process for the NC7, with the aim of redefining the application criteria, of upgrading the standards for measurements and of introducing more severe requirements, in terms of lower limits for noise levels in the various spaces on board and of better insulation indexes for walls. This update was in line with the modern needs for increased comfort and better working conditions for workers and with the improved technologies available for noise control on board. The final version of the new Code is contained in Resolution MSC.337(91), scheduled to entry into force on July 1st, 2014. Not all the reductions in limit levels that were proposed in the working group were actually approved, but the general trend of improving the acoustical performances of the internal spaces of ships has been maintained. The Noise Code (both in the previous and in the future version) applies to all major ships in service, (with the exception only of very specific categories of vessels). The focus is on the crew health, even though mention is made, too, to the enforcement of safety through audibility of signals and of commands. Three types of provisions are contained in the document: (a) limits on A-weighted noise level for various spaces on board (‘instantaneous’ levels); (b) noise exposure limits, setting a limit for the equivalent average noise level $L_{eq(24)}$ on 24 hours; (c) minimum insulation indexes for partitions between different spaces on board: bulkheads and decks.

Comfort Classes (CC) were issued (with different degrees of details) since the ‘90ties by the various CS to rank the acoustical performances of ships. Requirements of the same type of those of the NC (but more restrictive) are formulated for maximum levels in dB(A) for each space on board. Prescriptions are formulated, too, for partitions, as in the NC, in terms of the sound insulation index of vertical walls (bulkheads), but also of the noise impact levels in cabins below horizontal subdivisions (decks). This requirement aims at reducing noise due to people moving on the deck (jogging, dancing or simply walking). Crew spaces (in particular cabins) have different limits from passenger spaces; for the former spaces, most of the CC refer (for the lowest grade) to the Noise Code.
2.1 Comments on existing requirements

The formulation of CC, devoted to the assessment of comfort, does not differ much, from a typological viewpoint, from the requirements of the NC for workers’ health. They both rely on merely energetic indexes, such as the A weighted sound level (even though with CC contain more restrictive limits). No provisions are set in the CC for noise exposure (levels combined with exposure time), present, on the contrary, in the NC. When dealing with the evaluation of the acoustic comfort, more refined indicators are available from other engineering fields, accounting for the spectral composition of noise and/or the repetition over time. These indicators could provide much more information about the sound wellness (intended as the human perception of the acoustic adequacy of a given space) and could convey more information able to help in identifying the interventions needed for improving the situation. What prevents, however, an immediate application of such indicators to the ship context is the lack of databases representing the state of the art in the field in terms of those indicators.

2.2 Next generation rules – prenormative requirements

On the basis of what above, a refinement of the assessment criteria for the acoustical performances of the internal spaces onboard ships can be obtained in the short term only using the same indicators contained in the present norms. This refinement should follow the general trend of lowering the impact of noise on working and living environments: this should be done balancing the perceived improvement in the acoustical quality of the ambient and the technological effort (and related cost) implied to achieve the target. The pre-normative requirements about internal spaces on board ships issued within the SILENV project were in fact derived on the basis of (a) the already existing requirements (and their band of variation if more formulations were available) (b) the state of the art of noise and vibration levels on board existing ships, obtained from pre-existent databases, integrated with a few ad-hoc measurements; (c) a survey of the subjective human responses (by categories) to actual (objective) noise levels, obtained by questionnaires compiled during voyages in which experimental surveys were also carried out; (d) a survey of the technical solutions available to improve the situation (with evaluation of their costs). The noise limits of Table 1 below were set for re-defined categories of internal spaces on board.

A feature of these limits is represented by the fact that no differences are made between crew and passengers (as regards f.i. cabins). These limits are always lower than those set in the compulsory requirements of the IMO code and are generally situated within the range of variation of the Comfort Classes requirements. The same applies to the requirements (not shown here) about the minimum isolation between cabins walls (present in both the existing sets of requirements).

Exposure limit levels for the crew (not set by the CCs) were made more stringent than in the IMO code, reflecting in this way the same trend in the reduction of levels. The impact noise levels (not covered by the IMO Code) were set to values within the range of values prescribed by CCs. As mentioned, the proposed limit levels were also compared to the levels measured in existing ships.

3. Noise emissions in air

Air noise pollution from ships affects people living near channels or coastal areas with intense traffic of ships passing by, or near ports, where ship enter and stay moored at quay for loading/unloading processes. The ship source, when sailing along coasts or channels, features characteristics in common with typical mobile sources like: road vehicles, trains, airplanes but, when moored at quay, it is also similar to stationary sources like industrial plants. Unfortunately, at present, specific instruments to characterize, assess and control the ship source type are not available and in many cases indicators are taken without adaptation from other sources categories, for which experience is larger.
Table 1. Noise and Vibration limits – SILENV pre-normative requirements.

<table>
<thead>
<tr>
<th>Group number</th>
<th>Group name</th>
<th>Location example</th>
<th>Noise Limits (dB(A))</th>
<th>Vibration limit (mm/s - rms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cabins</td>
<td>Passenger cabins</td>
<td>50</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Crew cabins</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hospital</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Offices</td>
<td></td>
<td>53</td>
<td>1.5</td>
</tr>
<tr>
<td>3</td>
<td>Public Space A</td>
<td>Libraries</td>
<td>55</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Calm public spaces</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Public Space B</td>
<td>Restaurant</td>
<td>60</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lounge</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mess room</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Shops</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Public Space C</td>
<td>Discotheque, dancefloor</td>
<td>65</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ballroom</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Corridor</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Staircase</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Outdoor Areas</td>
<td>Open recreational area</td>
<td>70</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bridge wings / Open deck working areas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Wheelhouse</td>
<td>Wheelhouse</td>
<td>60</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Radio room</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Work space A</td>
<td>Engine control room</td>
<td>65</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Galley</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Work space B</td>
<td>Pantries</td>
<td>75</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stores</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Laundries</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Workshops</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>garage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Work space C</td>
<td>Continuously manned machinery space*</td>
<td>90</td>
<td>2.5</td>
</tr>
<tr>
<td>11</td>
<td>Work space D</td>
<td>Not continuously manned machinery space*</td>
<td>105</td>
<td>3</td>
</tr>
</tbody>
</table>

* Hearing protection mandatory

In both cases (ship as mobile or stationary source) the impact of the radiation depends on the characteristics of the surrounding area (orography, distribution of buildings and of population). In other terms, both the receivers at the end of the airborne transmission path and the transmission path itself are external to the ship and independent from the ship characteristics. This makes the normative framework on external noise different from the case of the noise internal to the ship (for which source, transmission path and receivers are all on board, depend only on the ship characteristics and are subjected to the same Normator). The situation is briefly recalled in the following (see also 11).

3.1 Existing norms

The airborne sound emitted by all types of vessel (except recreational crafts) is covered by 12, both in sailing and moored conditions. For moving vessels, the descriptors adopted are the A-weighted sound exposure level, $L_{AE}$, and the maximum AS-weighted sound pressure level $L_{pASmax}$, while, for stationary vessels, the time-averaged A-weighted sound pressure level, $L_{pAeq}$, is adopted.

Recreational crafts of different types with length up to 24m are also covered 13 (only in the sailing condition). The procedure foresees to report the maximum AS-weighted sound pressure level during the passage ($L'_{pASmax}$) and the same quantity corrected for background noise and distance ($L_{pASmax}$). The evaluation of $L_{AE}$ is optional. A second part of the standard specifies a comparative procedure to assess the maximum sound emission of powered mono-hull recreational crafts using the concept of reference craft. Both the above standards refer to measurements carried out at ground level. All these measurement standards are mainly aimed at carrying out acceptance and/or monitoring tests. Maximum source levels of inland vessels are covered in the European directive 2006/87/EC: these limits are of 75 and 65 dB(A) under way and in moored conditions, respectively; both are to be verified at ground level, at a distance from the side of 25 m.

In order to analyze and control the environmental noise pollution the European Commission introduced the Environmental Noise Directive 14, (END). It introduced a very useful tool of acoustic planning in order to analyze and to control the environmental noise pollution: the Noise Strategic Mapping (NSM). Day-Evening-Night Level ($L_{den}$) and Night Level ($L_{night}$) are the noise indicators recommended for the mapping. Annex IV explicitly cites ports among the locations where an NSMs should be developed. The noise emitted by ships is one of the main categories of noise which must
be taken into account during a port NSM\textsuperscript{15}. Members States should transpose this Directive into National Laws; in the meanwhile, previous national regulations are still in force, where limits are expressed in terms of other indicators (often equivalent sound pressure level weighted $A$, $L_{Aeq}$, with various reference time periods changing from country to country). For a review of policies in the field of noise control in ports, see\textsuperscript{16,17,18}.

### 3.2 Comments on the existing measurement standards

The ISO Technical Standards above mentioned don’t aim at a proper acoustic characterization of the ship but define procedures for acceptance and monitoring tests. The application of the NSM concept, on the contrary, calls for a proper acoustic characterization of the sources and, in the specific case of NSM of ports, ships are the most relevant sources (even though not the only ones).

There are specific features of the ship source that make difficult a proper characterisation. Ships are very large sources of noise, particularly if compared with the local geography of the sites to be evaluated. They also feature a strong directivity, as pointed out by experimental as well as numerical investigations carried out within the SILENV Project\textsuperscript{19,20}. These characteristics are particularly relevant for studying the impact of moored ships, for which the interest may be focussed 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 characterise completely the source\textsuperscript{21}.

Sailing ships move in a relatively free field, at larger distances from potential receivers, so that the near field effects and the interaction of the emitted sound with obstacles are less important for the purpose of the prediction of propagation patterns. In addition, the characterisation of the sailing ship, is unavoidably carried out at a large distance which, for practical reasons, will be higher for larger ocean going vessels.

### 3.3 Proposed procedure for the characterisation and pre-normative requirements

In the light of what above, the objective of a more complete acoustic characterisation of the moored ship source, to be possibly used for an accurate prediction of the external sound propagation, was pursued in the SILENV Project. A set of measurements, additional to those recommended by the existing Standards, have been identified. Such measurements are 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. 1).

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, without the need for applying 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. The same procedure as in the European directive 2006/87/EC was adopted for the characterisation of the sailing ship, with an increased reference distance.

![Figure 1 Grid of points for the characterisation of airborne radiated noise (SILENV)](image)
4. Noise emissions in water

The problem of underwater radiated noise (URN) from commercial vessels has been addressed only very recently, with reference to the impact on the marine fauna. Anthropogenic noise in general can affect the life of marine animals causing them to abandon their habitat or to alter their behaviour or masking acoustic signals emitted for eco-localisation or communication purposes\textsuperscript{22}. Higher sound levels could even affect hearing capabilities of aquatic animals, producing either temporary or permanent hearing losses\textsuperscript{23}, but these more severe consequences are rather related to other kinds of anthropogenic noise sources than ship traffic, (e.g. sonars or underwater explosions. A proper quantification of the actual impact of URN from a ship implies a characterisation of all the elements involved (source, transmission path and receiver). Propellers are most likely the major source of underwater radiation from ships: they are placed at the extreme aft end of the hull and, accordingly, high noise levels can often be found behind the stern, where the direct radiation from propeller and the noise reflected by the stern counter sum to each other’s. Further contributions to the global radiation may come from the main and the auxiliary engines. The transmission of noise in the sea is influenced by many parameters, such as: the celerity profile in the water column, the composition of the bottom, the relative position of source and receiver and the sea roughness. The combination of all these parameters generate complicated transmission paths, depending on frequency, too. Finally, the impact on the marine fauna is related to the hearing capabilities of the various species, but in some cases also emitting characteristics can be of relevance (as in the case of interference with communication between individuals).

4.1 State of the art in the characterisation of source and receivers

URN from ships has been studied since a long time in the military field, but with very different purposes, and anyway results are often not available due to security restrictions. Recently, however, the characterisation of the ship source has been sought also for commercial ships. Two main standards are today available. The ANSI/ASA standard\textsuperscript{24} offers three grades of open sea measurement, differing in terms of complexity, uncertainties and repeatability: the number of hydrophones to be deployed varies between 1 and 3, while in the DNV\textsuperscript{25} procedure only one hydrophone is placed on an inclined sea bed. In both cases, the vessel at design speed is supposed to pass at a measured distance from the hydrophone both on starboard and port side. The ship is modelled as an omni-directional point source and results are presented in terms of levels in 1/3 octave bands ranging from 10 Hz to 10kHz referred to distance of 1m. Simplified transmission laws (different in the two documents) are used to normalize the distance. The above measurement procedures are based on a model (omni-directional point source) which does not fit very well with the characteristics of the ship noise source. Further, the post-processing procedures of surveys do not take into account most of the various environmental effects (water column characteristics, reflections from bottom and free surface) that can influence the noise propagation from source to hydrophones. This poses a problem of uncertainty in the source characterisation during sea trials\textsuperscript{26}. The same kind of uncertainties affect the prediction of the propagation from the source to the potential receivers (located at higher distances). As regards reference limits for the URN, DNV\textsuperscript{25} suggests curves for different classes of ships. The background of such limits is not explicit in the text, but is probably derived by noise surveys carried out on state-of-the-art vessels. A different and interesting approach was earlier followed by the International Council for the Exploration of the Sea (ICES), when elaborating URN limits for fishing research vessels\textsuperscript{28}: such limits are (to some extent) based on the cod’s sensitivity to noise, their aim being to ensure that a vessel could approach fish stocks without scaring them. An important set of receivers for the UWN radiated is represented by marine mammals. Hearing sensitivities are available for the smaller species (e.g. dolphins), but not for the Mysticetes, due to their dimensions and inherent difficulties in carrying out lab tests\textsuperscript{29}. 
4.2 The SILENV proposal for URN limits

A proposal for limits to the URN from commercial ships was developed within the SILENV project\(^9\), based on: (a) existing requirements in the field; (b) state-of-the-art of the European fleet as evaluated by the project database. Due to a lack of data in the noise effects on many species, the criterion adopted was to account for what technologically achievable according to the state of the art as derived by the SILENV database, more than for the minimisation of the actual impact on marine animals (that was not possible to evaluate). Also in the format, these limits are similar to the existing ones\(^{25,28}\), being represented by levels at 1 m vs. frequency (Figure 2).

Peculiarities are represented by the fact that no distinction is made among different ship types and that two limits are provided, for design speed and reduced speed (quiet) conditions. The first aspect is justified because the impact on marine fauna is not dependent on the ship type, the second one is a key point for implementing noise control by operational constraints (speed limitation).

5. Conclusions

The state of the art of the evaluation of the impact of the above analysed three types of noise radiation from ships (towards internal spaces, outwards in air and outwards in water) is quite different and this is reflected, too, in the different degree of development of the normative frameworks set up for the three contexts. Such different situations depend also on the time elapsed since the various types of radiation have been recognised to have a negative impact. Questions are still open in all the three fields and it is foreseeable that important developments will take place on the short and long term in the norms aimed at the control of ship noise emissions in the various environment affected.

Short term implementations are limited to the use of the present knowledge and technologies, and can be sought improving procedural aspects, f.i. those related to the characterisation of the ship as source of external noise. The model of a single omni-directional point source for external radiation (both in air and in water) seems to be ready to be substituted by more elaborate models (more points and/or directivity patterns); the same applies to the evaluation of the human perception of noise on board, which could take advantage of more detailed indicators than the dB(A) levels. A more fundamental research work is needed, however, on the quantification of the actual impact of URN on marine fauna, in particular on large mammals, for which large dark areas are still present.

Acknowledgments

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