The greatest challenge for URN reduction in the oceans by means of engineering.

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***Abstract*— The Underwater Radiated Noise (URN) of the oceans due to shipping activity has increased during the last decades. This significant increment of URN can be explained by the remarkable growth of maritime traffic in recent years and the greater number of seismic explorations in the oceans. In relation to this issue, the current elevated level of underwater radiated noise in the oceans is producing a negative impact on marine fauna as it is happening with the Southern Resident Killer Whale (SRKW) in the Salish Sea in the west border between Canada and the USA. In the short-term, these high levels of URN block animal's ability to communicate, navigate, reproduce or hunt; while in the long-term, it may cause hearing loss in them. Hence, it is urgent to control the elevated level of URN in the oceans to protect the marine fauna and ensuring the sustainability of the sea environment.**

The majority of the underwater radiated noise produced by ships in the oceans originates from propellers, engines and auxiliary machinery. The International Council for the Exploration of the Sea (ICES) Report Nº 209 was created with the aim to establish certain limit values on the URN generated by ships. The main purpose of this analysis is to avoid the negative effects of the URN on the sea environment and protect to the marine fauna of the vessel echosounders interferences focusing on the design and build of silent ships by means of a noise and vibration comprehensive management methodology.

The scientific community has demonstrated that the anthropogenic noise produced by the shipping sector is the main responsible for the relevant growth of the URN in the oceans which causes negative effects on marine life [2]. As a result, a benchmarking study has been addressed by Canada to inform about the negative impacts of URN in the marine environment and propose the creation of new regulatory policies on URN reduction. This exploratory study has been carried out by a specialized steering committee which is composed of a network of organizations with a proven record in R&D and innovation activities in shipping URN. This technical study is in line with IMO conclusions for the reduction of URN from commercial shipping to address adverse impacts on marine life (MEPC.1/Circ.833; MEPC 74/17/2; MEPC 74/INF.36) representing the greatest challenge for the protection of the marine fauna in the oceans.

To deal with the challenge of URN reduction in the oceans, the technological experiences accumulated over the years in the dynamic and acoustical design of modern Fishing Research Vessels (FRV) and Oceanographic Research Vessels (ORV) can be extrapolated to the rest of marine sectors.

The main objective of this study is to identify which type of actions can be potentially used to manage and minimize URN generated by ships in the oceans without affecting the marine traffic and the transport of goods. The main idea is to design a new generation of "Silent Ships" in compliance not only with the strictest Comfort Class Notation requirements but also with the most restrictive URN requirements such as ICES Nº 209. The overall URN level of a ship at certain operational speed is the combination of the noise spectral component generated by different URN sources such as the main engine and the propeller. Consequently, the reduction of the overall URN level will imply preventive actions for each one of the dominant URN sources. In summary, it can be concluded that a drastic reduction of the underwater radiated noise in the oceans is of vital importance to guarantee the sustainability of the sea environment and protect marine life. Thus, it is necessary to promote the design of a new generation of silent vessels using the most advanced engineering technology developed for the minimization of URN.

***Keywords*— marine, noise, silent, URN, engineering, vessels, whales, thresholds, standards**

I. Introduction and Context

The Underwater Radiated Noise (URN) of the oceans due to shipping activity has increased at least 19 dB during the last five decades [1]. This significant increment of URN can be explained by the remarkable growth of maritime traffic in recent years as well as the greater number of seismic explorations in the oceans and other engineering activities related to the blue economy (renewables marine platforms, etc.).

The current high level of anthropogenic URN in the oceans is producing a negative impact on marine fauna (i.e. whales, dolphins, sharks, fish). As an example, this situation is happening with the Southern Resident Killer Whale (SRKW) in the Salish Sea in the west border between Canada and the USA. There is a real concern about the marine traffic and how is the effect of it on this sort of whales. URN is one of several factors contributing to the at-risk condition of the SRKW population inhabiting in this location, in which many vessels are operating to import and export goods as well as transporting and employing large numbers of people. It is a fact that marine traffic in short-term is affecting the population growth of this species due to its interference in their navigation, communication, hunting and reproduction activities, resulting in a decrease of the number of them in this marine spot. At the same time, in the long-term, it may cause hearing loss or the loss of the SRKW community as well as the rest of marine wildlife in the Salish Sea.

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From the authors' knowledge, Canada is addressing this issue considering all the players involved from the point of view of mitigation measures. Canada is promoting the anthropogenic URN issue in IMO (International Maritime Organization) and engaging other countries with the support and advice of experienced engineering companies and biologist community in order to achieve trade-offs in benefit of the marine fauna and the shipping sector.

Despite the essential importance of the maritime sector in the economy and well-being of the society living in port surroundings, current vessels are a relevant contributor of URN due to the huge number of them all over the world, their time on the water emitting noise and their configuration of operation. For instance, a ferry operating at service speed is typically measured to be emitting URN at a broadband sound intensity of around 180-185 dB [3]. Furthermore, the quantitative studies within the science community indicate that vessels operating through the Salish Sea at sound intensity above 175 dB are the primary candidates for reducing overall noise levels in this SRKW critical habitat [4].

This circumstance has been analyzed thanks to the large experimental campaigns, studies and efforts carried out in this area and for sure, it can be extrapolated to the rest of the coast line all over the world, diminishing the biodiversity and rising the underwater noise pollution of these areas without control. Thus, and considering the seemingly low concern of policy-makers on this matter, it is urgent to adjust the current elevated level of URN in the oceans to protect the marine fauna and ensuring the sustainability of the sea environment. From the point of view of engineering, this improvement of the sea environment can be addressed by means of noise, vibration and URN control in vessel design and construction.

Noise, Vibration and URN requirements are nowadays included in the majority of Technical Specifications of experienced shipowners of fishing research vessels (FRVs) and oceanographic research vessels (ORVs), however, these requirements are barely considered in the rest of sort of vessels except for military vessels. A proper Noise & Vibration (N&V) control methodology might result in a low emission of URN emitted by a vessel, following a set of recommendations and steps according to the methodology described below. The methodology considers the vessel design, the shipyard itself, main machinery and propeller suppliers, among other issues, such as acceptance criteria as well as monitoring of the whole process from the earliest stages of the design, during the building stage and until the official sea trials. This methodology has been part of a cumulative conclusions and findings obtained over the years designing FRVs and ORVs as silent vessels, and extensively validated by means of on-board measurements and testing campaigns [5][6].

Obviously, in order to be able to achieve the goal of silent vessels, it is a need for the naval architecture and maritime sector that regulatory bodies and policy-makers set an international regulatory framework with the contribution of the biologist community, which should define and harmonize the underwater noise thresholds acceptable to marine fauna in all frequency ranges. These game rules for all stakeholders all over the world would be the precursors of the boundary conditions of this silent vessel technology and its potential development.

In this regard, the main objective of the present paper is to explore the challenges faced by all players related to the vessels design, construction and operation in terms of reduction of URN and provide an overview of the state of the art of the current URN standards, engineering solutions available and the author's proposal for the reduction of onboard N&V and underwater noise signature of new vessel constructions.

II. State of the art of URN measurement regulatory framework

It is a matter of fact that in spite of various initiatives and intentions to introduce control of URN, these did not become commonly used by industry. The exceptions are two categories of vessels: military vessels (including submarines) and FRVs/ORVs. Military vessels due to tactical advantage that silent performance provides, despite the state of the art in this field is advanced, all information is considered classified and there is no possibility to use it for civil vessels. The second category is FRVs/ORVs, in which N&V and underwater acoustic signature is regulated by ICES 209 [7]. This specific requirement was defined with two objectives in mind: increasing effectiveness of echo-sounders and reducing impact on marine fauna to be researched.

Unfortunately for the rest of vessels paradigms are the following ones:

- There is no agreement among biology scientist community on URN thresholds.
- There are no homogenized limit values among regulatory bodies and Classification Societies.
- There is no harmonization in measurement procedures and consecutive data post processing among regulatory bodies and Classification Societies.

In the following subsections is given a brief description of several measurement methodologies and limit values depending on the regulatory body:

1) *ICES CRR Nº209.*

It represents the first URN regulation of Research Vessels (such as ORVs or FRVs) in the framework of civil ships and it was released in 1995 by ICES (International Council of Exploitation of the Sea) and a high restricted requirement in the maritime sector in terms of URN [7]. Based on more than 40 years in biological research of this institution, it was stated the recommended underwater acoustic signature target limits detailed in Fig. *1* from 10 Hz to 100kHz for the free-running speed of 11 knots, the main common speed and operating condition for acoustic survey through echo-sounders, to ease the comparison of vessels under this standard. These limits, with two different slopes for two specific frequency ranges, were defined to ensure the optimal performance by avoiding the disturbance of the targeted fish species subject to observation (limit in the frequency range from 10 Hz to 1kHz) as well as the interferences in the echo-sounders (from 1kHz to 100 kHz). Other operational conditions (speeds) can be considered, in order to be able to quantify the influence of machinery and construction solutions that had been used and imply lessons learned to improve future vessels.

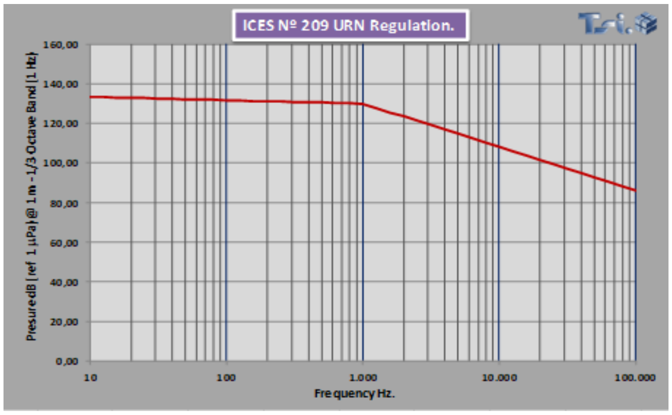

Fig. 1. ICES Nº 209 Regulation. URN target limits for FRVs (Source: TSI)

2) ANSI/ASA-2009.

It was the first attempt to standardize the URN measurements procedure [8]. It addresses measurements of the underwater sound pressure in the far field and deep waters (depth>75m) to follow spherical attenuation and avoid reflections. Thus, the transmission loss (TL) considered is $20*Log_{10}(R)$, where R is the distance from the vessel to the hydrophone. The procedure selected has no inherent limitation with regards to the vessel size and mainly considers the hydrophone array connected to the seabed, taking into account three levels of measurement precision. It states that it is necessary to use 3 hydrophones and its recommended depths are related to the distance of the vessel to them and a set of angles of noise signal. ANSI-ASA does not define targeted limits.

3) ISO-17208-1.

On 2016, ISO (International Standard Organization) released the standard [9], corresponding to the first part of the standard, in which it is considered deep waters URN measurements (depth>150m). It has been completed recently through Part 2, and the expected Part 3, which is related to shallow waters measurement (depth>30m), is in draft version. The method is limited to ships transiting at speeds no greater than 50 knots (25,7 m/s) and the frequency span is between 20Hz and 20kHz. The measurement method smooths the variability caused by Lloyd's mirror surface image coherence effects, nevertheless, does not exclude a possible influence of propagation effects like bottom reflections, refraction and absorption. No specific adjustments for these effects are provided in this part of this standard focused only on measurement in deep waters. Number of hydrophones, their depth and TL is the same as ANSI/ASA standard.

4) DNV- SILENT Class Notation

On January 2010, DNV published the Silent Class Notation [10] as a standard for the URN measurement emitted by ships. This standard specifies targeted limits and associated measurement procedures for shallow waters (depth>30m). Depending on type of operation of the vessel the Classification Society provides different type of Notations: "A", "S", "F" and "SILENT-R", being the last one for vessel engaged in research or other noise critical operations. The URN limits for the "R" category are similar to those required by ICES CRR Nº209. Regarding to measurement procedure, the following points are highlighted: (i) only one hydrophone deployed practically on the seabed is employed; (ii) the speed/s at which the vessel shall be tested is based on the vessel operational speed profile for typical hydro-acoustics operations; (iii) two runs (one for each side of the vessels) are required; (iv) is considered only one data window, being of one or two vessel lengths, depending on the vessel speed; and (v) TL parameter used for distance correction is calculated according to $18*Log_{10}(DCPA)$ and a correction of minus 5dB applied due to surface reflections, where *DCPA* stands for Distance of Closest Point of Approach. A scheme of the measurement arrangement is shown in Fig. *2*.

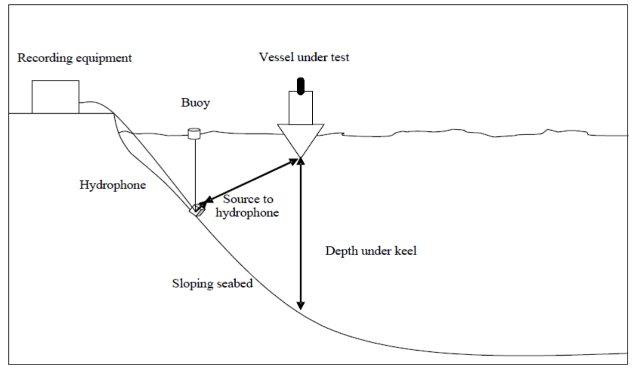

Fig. 2. DNV-GL SILENT URN Measurement Procedure (Source: DNV-GL)

5) BV-NR 614 URN Notation.

Bureau Veritas (BV) issued in October 2014 its URN Notation, BV NR614 [11], which addresses both deep water (depth>200m) and shallow water (depth>60m) measurements. Two schemes of both measurement configurations are shown in Fig. *3*.

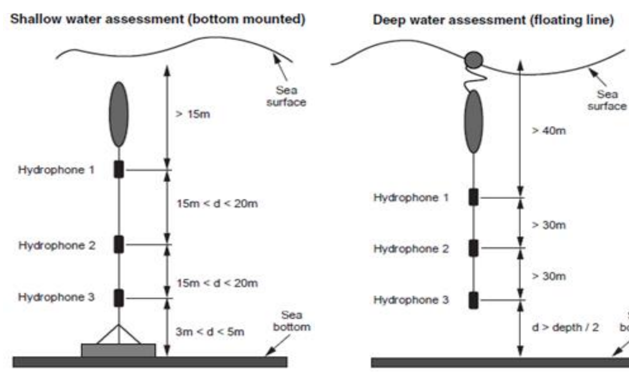

Fig. 3. BV-NR 614 URN Measurement Procedure (Source: BV)

With respect to the measurement procedure, the following points are highlighted: (i) an array of three hydrophones is considered distributed according to a set of distances between them by means of two configurations depending on the depth; (ii) measured speeds are according to operational conditions of the vessel; (iii) it requires three runs for each side of the vessel; (iv) it considers 19 data windows of one vessel length or 100m, whichever is greater, being the recording length of 1600 m; and, (v) TL is calculated depending on the depth, being $19*Log_{10}(D)$ for water depths below 100 m and $20*Log_{10}(D)$ for water depths greater than or equal to 100 m (*D* is the distance from the vessel to the hydrophone). The post-processing of the data allows a good adjustment from the statistical point of view due to the massive data obtained with each URN measurement (19 data windows, 3 hydrophones and 6 runs). In this standard, measured values are analyzed without the subtraction of 5 dB as in DNV-GL.

There are other URN rules such as GJB4057-2000 (Chinese rule) as well as others from the rest of the main Classification Societies, which have been released lately: Rina Dolphin on July 2014, LR on February 2018 and ABS on July 2018. Most of these class notations have adopted, to a greater or lesser degree, the corresponding URN measurements procedures defined by ISO and ANSI/ASA.

Generally speaking, the intended objectives of URN measurements rules are: (i) to show compliance with contract requirements defining a standard of URN; (ii) comparison of vessels underwater acoustic signature; (iii) set periodic acoustic signature assessments; and (iv) carry out research and development activities. In conclusion, it can be said that these objectives will not be met if URN data postprocessing methods differ from each other, as well as measurement methodologies. It is was found by the authors that for the same URN measurement were obtained different results depending on the regulatory body used for postprocessing and thus the same vessel evaluated by different body would obtain different results.

III. NATURE OF THE URN BY VESSELS

The underwater acoustic signature of a vessel is defined by the broadband URN emitted by it. The frequency broadband of URN is at the same time defined by the different noise sources of a vessel and the paths followed by them through the air and the structure to the water [12], *i.e.* the main power plant and the auxiliary machinery of the machine room (both structureborne and airborne), the propeller, thrusters and any other equipment of higher or lower operating frequency on board along with the noise produced by the interaction of the fluid with the structure and propeller (hydrodynamic noise and other fluid noise phenomena such as cavitation, tank sloshing, slamming or bubble swipe-down). All these URN sources can be gathered in three key groups: (i) hydrodynamic noise produced by the fluid against the structure and propeller; (ii) structureborne noise due to mechanical vibrations; and, (iii) airborne noise. Fig. *4* shows as an example a scheme of the main vessel noise sources described above.

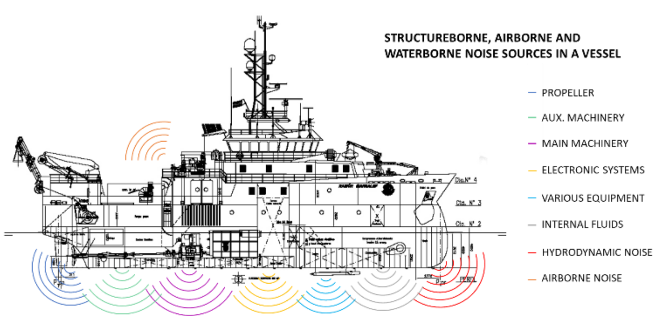

Fig. 4 Vessel noise sources (Source: TSI)

Considering that sound propagates faster in water than in air and the low absorption rate of water (which depends on density, temperature, pressure, salinity, etc.) makes noise produced by vessels traveling huge distances in the open sea, especially low-frequency noise. The URN low frequency emitted by the machinery, propeller and other equipment of the vessels (frequency broadband of 10Hz and 10kHz), is the principal problem for the marine fauna (particularly for whales and fish) due to its coincidence with whistles and clicks, which confuse most of cetaceans and hamper their natural biological activities.

In order to be able to analyze the URN issue as a whole from the point of view of engineering, the Shipping sector and marine environment, there is a set of challenges to be overcome to move forward in the development of vessel URN reduction technology.

One of them are engineering improvements to be adopted and researched in the vessel design to reduce the URN emissions. These improvements and good practices should be addressed by shipowners and shipping companies; however, consistent and clear rules and standards must exist regarding the URN limits to allow all stakeholders to be on equal terms and without affecting their competitiveness. As it was abovementioned in a previous section, there is a lack of international regulatory framework; nevertheless, the strong commitment of Canada in the promotion of the development of a regulatory framework in IMO gives a good perspective of the future in this regard, laying the foundations of the requirements to mitigate URN and develop vessels more technological and of higher added value.

Another of these challenges is the lack of noise and vibration information of the sources from suppliers as well as the lack of enough experimental data of the URN of vessels. As stated by *M.F. McKenna et al., "broadband acoustic measurements of radiated noise from individual modern ships under normal operating conditions are needed to advance our understanding of the contribution of shipping noise to the marine environment*" [3]. Considering this study, as a good reference for understanding the URN emitted by a set of commercial vessels, it is interesting to analyze obtained results to have an idea of the level of noise depending on the class of vessel and their main operating speed.

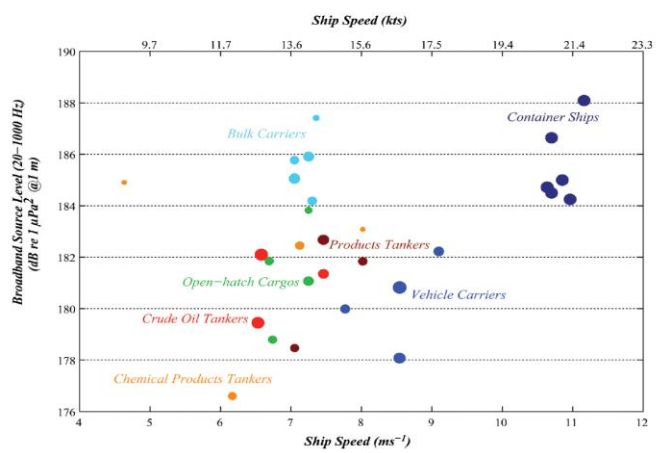

Fig. 5 Broadband ship source level versus speed for measured ships. (Source: [3])

Fig. *5* displays the relationship between the URN as SPL (Sound Pressure Level) within a frequency broadband of 20-1000Hz and the ship operational speed for a total of 29 commercial vessels, using the color and size of the data points as the vessel type and dimensions of the commercial ships, respectively. From this figure, it is difficult to obtained URN tendencies according to the vessel class, displacement and speed; nevertheless, some conclusions can be found:

- Containerships navigating at around 20kn reach an estimated SPLs of 186dB while bulkcarriers of less length and navigating at around 14kn produced the same URN, despite engine power of containerships are around 4 times higher. Several reasons may explain this difference, such as the vessel design & construction quality, typology of the power plant and its integration in the structure or the shape of the hull and its block coefficient; nevertheless, the statement that low speeds produce low URN values (which is generally true for the same vessel or even the same type of vessel) cannot be assumed in this comparison.
- At the same time, if the group of bulkcarriers is compared with crude oil tankers of similar length, speed and engine power, it is noticed that URN of this second type of vessels generates around 181dB, which means 5dB below with respect to the SPL average value of the set of bulkcarriers.
- And, these crude oil tankers in comparison with the group of vehicle carriers, with higher engine power and speed and less length, produce more or less the same average level of URN (around 181dB)

It is clear that URN signature of vessels is strongly influenced by the ship type – which inherently implies design particularities - which should be taken into consideration in definition of the underwater noise thresholds to be met by each sort of ship. Additionally, these thresholds must consider also the technological state of art and cost of solutions to be implemented as well as their impact on operations. The shipping sector stakeholders and marine biologists must reach trade-offs in the consecution of the main goal: underwater noise reduction to avoid negative impacts in the oceans.

IV. Triggers of Change and Potential Effects in the Market

Considering that there is a lack of URN thresholds, homogeneous measurement procedures, measured data postprocessing, lack of experimental URN data of existing vessels, and no mandatory requirements, it is obvious that URN is not a palpable problem for shipowners and ship operators, focusing their efforts on other important matters regarding environmental sustainability such as greenhouse gas emissions or ballast water treatment management. Furthermore, this situation produces confusion in designers, shipbuilders and end-users, making difficult to set a standard of quality in terms of underwater acoustic signature.

The exception are military vessels due to their need of undetectability as a tactical advantage that a silent vessel provides; likewise, FRVs and ORVs and their own standard [8], defining requirements for a type of vessel in which the low levels of URN are critical for operating of onboard installed investigation equipment and also to not disturbing and scaring away the marine fauna.

Nevertheless, increasing environmental consciousness and public pressure against the negative impacts of submarine noise pollution on marine fauna is fostering changes in regulatory framework by means of regulatory bodies, promoting both international and local initiatives, such as European Commission with Directive 2008/56/EC and Vancouver maritime area (Canada) as the best example.

Once the new regulation will come into force, new build vessels shall adopt measures to reduce URN. However, the current fleet of existing vessels will remain still for a long time in operation and, being realistic, "as they are" in terms of N&V. It is clear that a trade-off must be reached and depending on the URN signature and the locations to be navigated, most of them will need to embrace gradually URN mitigation measures to be able to perform their usual economic activity without producing environmental negative impacts.

As a possible future scenario, the creation of noiseless navigating zones is forecasted, in which navigation should be limited for the vessels with a URN signature within the permitted thresholds, enabling the operation of silent vessels in these zones without restrictions while the rest of them would be forced to reduce the effect of URN in these locations through two possible ways:

- Limiting significantly the vessel speed in the proximity and along these noiseless navigating zones.
- Deviating the vessel course a specific distance away from these protected areas.

These actions will imply for noisy vessels the increasing of operational costs (mainly bunkering costs), delays on cargo delivery and loss of competitiveness regarding freight rates, producing a reduction of the ship operation capacity and cost-benefit efficiency. In both cases, "how much distance away" and "how much speed reduction" are technically undefined so far, and it is expected to be solved in the coming years by the forthcoming international regulations, future R&D projects focused on this topic and the view of maritime stakeholders.

For existing vessels, regardless of the contract typology of them, *i.e.* regular line vessels (mid- or long-term contracts) and tramp vessels (spot contracts), an economic study will be necessary to find out the steps to follow for each shipowner or ship operator. In the case of regular line vessels, firstly, it will be necessary a study of usual routes, analyzing whether the route crosses these noiseless navigating zones. Secondly, a cost analysis should be performed considering the expected URN standards and the cost of the implementation of URN reduction solutions, and comparing it with the potential cost of not addressing the vessel underwater noise signature adjustment to the URN thresholds. If the total impact of the initial extra cost of adopting URN mitigation measures is lower than the first cost, the investment should be considered depending on the vessel's remaining life-cycle and the potential loss of competitiveness that might arise.

This hypothetical situation described above is quite similar to the current situation faced by the maritime sector regarding shipping gas emissions produced by vessels bunkered with high sulfur content fuel. Two main possibilities were raised: (i) using low-sulfur fuels (more expensive than high-sulfur fuels) or (ii) installing of scrubbers in the vessel exhaust system (with an overall cost approximately between 2-4M€).

On the other hand, for new vessel constructions, the combination of the clear conditions defined by potential expected URN standards and the abovementioned operational limitations to navigate in protected areas (with significant impact on the economic exploitation of the ships), will highly motivate the shipowners in shifting their approach for their future ships in order to increase their competitiveness.

Lately, URN analysis is starting being considered as a vessel performance parameter in the commercial marine sector to meet high standards and quality, and fortunately, URN measurements are being more common in recent times, despite they are not mandatory. Apart from military and research vessels, the inclusion of silent clauses in a shipbuilding contract might be incorporated as an act of goodwill with the environment, a specific need due to a design requirement or a prevention/anticipation effort to future underwater noise regulations.

Consequently, in order to know the vessel quality and its expected impact in terms of URN on the ocean and its marine fauna, it is proposed to provide underwater radiated noise identification cards (URN ID) to vessels operating worldwide associating this identification with their IMO numbers. By means of this URN ID, it will be possible to include the underwater noise signature of the vessel in AIS (Automatic Identification System) or any other navigational and communication system of interest, allowing the access to this information to everyone and enabling the vessel monitoring as it is possible now with the position (GPS), speed and other relevant information of the ship. This system might bring three distinct benefits from the point of view of URN control: (i) regulatory bodies will be able to check the sustainable behavior of shipping companies and ensuring that the rules are being complied with, for the good of the marine environment and the competitiveness between shipping companies; (ii) in the case that permanent URN measurement systems are installed in selected locations and they compare automatically the measured values with the values in the URN ID of the vessel, the fleet managers of shipping companies will be able to take decision based on monitoring the URN of their vessels using this indicator as a health parameter of the vessel, because changes in the patterns of URN can give an idea of problems on board of different kinds (depending on the frequency of the noise change); and, (iii) it will be possible to gather URN data for statistical, biological and economic analyses and studies, in order to understand better this phenomenon and its implications in the shipping market and the marine environment.

V. Noise and Vibration Comprehensive Management (N&V-CM) Methodology

Based on successful results provided by the application of the Noise & Vibration Comprehensive Management methodology on seven research vessels projects (FRVs and ORVs) with the strictest onboard noise & vibration and URN requirements established by ICES 209. From author's point of view, for a positive result it is necessary to include the URN mitigation procedures and engineering solutions in *ALL* phases of the project of the vessel design and shipbuilding. As a summary, Fig. *6* shows the 4 main stages considered in this validated methodology for new vessel constructions.

Fig. 6. Stages of N&V Comprehensive Management methodology for new vessels construction (Source: TSI)

These stages of N&V-CM are summarized below:

1) Project definition stage: vessel specification and design

This stage is essential for the success of the project. An assessment from the N&V point of view must be carried out in the specification of the vessel project, the structural design, noise insulation and suitability of specified machinery, among other parts of the contract. It is absolutely mandatory that requirements regarding URN and onboard Noise & Vibration for this new vessel are defined in the vessel specification and is not recommended a vague reference to ISO or IMO rules. These requirements should be based on results from the preliminary assessment of the existing fleet, the vessel dynamic characterization including onboard noise and vibration prediction & measurement, existing and expected future regulation, comfort criteria, classification society, technological state of the art, N&V limits of the outfitting for its purchasing, and cost-benefit analysis of the selected choices with the possibility to include URN measurement to verify the compliance of the vessel with the selected standard and/or URN prediction. In this regard, these requirements will be part of the contractual conditions of the new vessel construction.

Therefore, this stage includes the analysis of the design criteria of the main N&V Sources and the establishment of contractual clauses in their purchase specifications. Considering that the main and auxiliary machinery along with the propeller/s are the main N&V sources, the suitable choice of them and the definition of specific dynamic and acoustical contractual criteria for these components become an essential and critical aspect to guarantee the compliance of the resulting vessel with the N&V requirements stated by the shipowner specification. In the end, the resulting level of vibration depends on the equipment itself as well as on the solution adopted for installation along with on the interaction of installed components.

Thus, it is necessary having noise and vibrations parameters of the main sources to be included in the structural dynamic modeling and prediction models of noise, vibration and URN considering the vessel structure and the abovementioned sources. These models are performed in two steps:

- Conceptual design: the objective of this step is to make sure that the new vessel is designed since the beginning with URN in mind. Decision making within this phase has a huge impact on the design, construction and operational complexity and costs. The underestimation of attention to detail during this step could lead to a situation in which the project will become too expensive or unfeasible to achieve the established URN goal. The complexity of this step is relatively low and it relays highly on the N&V performed analysis, which is related to the general distribution of the vessel and conceptual selection of the main machinery and its auxiliary equipment that has a significant emission of noise or vibrations. These recommendations should be considered in the ripening process of the vessel GA (General Arrangement) and preliminary structure drawings.
- Detailed prediction of vibrations, onboard noise and URN: once the structure of the vessel is defined, and having the dynamic parameters of the main sources of noise and vibration, it is feasible to create prediction models of noise and vibration levels along the vessel as well as the total emitted URN. The results of these calculations are used as (i) input for changes in structure, distribution of the vessel or even in type of equipment to be installed if it is necessary; (ii) input for optimization of the insulation installation; and, (iii) as baseline for following stages of the project until the vessel sea trials.

2) Purchasing stage

This stage is focused on the sensitization of equipment suppliers to allowed noise and vibration levels and the shipyard´s request of quotation of the needed equipment considering these levels. Suppliers contribution to the full success of the vessel project is beyond dispute. Their equipment, *i.e.* main and auxiliary machinery, propeller, thrusters, HVAC, accommodation panels, insulations, etc., must meet with the contractual requirements in terms of vibration and noise to be purchased by the shipyard. Suppliers must be able to provide N&V data and spectra to justify fulfilling the limits requested in the contract. This stage starts before the building stage to consider lead times, nevertheless, both stages are sometimes overlapped.

Furthermore, the information provided by equipment suppliers is also used to improve the prediction models of onboard N&V and URN performed in the previous stage.

3) Building stage: control and corrective actions

This stage is related to the control of the correct vessel construction from onboard N&V and URN point of view. The activities to be performed in this stage are summarized in the following steps:

- Factory Acceptance Tests (FAT) and Site Acceptance Tests (SAT): The objective is the verification of the compliance of the supplied equipment with respect to the contractual requirements defined in the project and purchase stages as well as be able to perform corrective actions in early stages. If this step is omitted, and in the case that the equipment to be installed does not meet the specifications, the final result will not correspond with the predictions.
- Inertance and mobility tests of machinery foundation: These tests are performed to ensure the proper installation, and to guarantee the absence of resonance phenomena in the foundations structure of the main and auxiliary engines once these equipment are integrated into the vessel structure.
- Airborne sound insulation index measurement: A set of tests should be carried out as soon as the accommodation begins to be installed in order to carry out corrective actions, in case of non-compliance results with regards to specification.
- On-site survey during accommodation and noise insulation assembling process: The achievement of the predefined target of noise on board is related not only to the suitable selection of noise insulation materials (according to the technical properties used in the simulations) but also to the right assembly of these components.

4) Sea trials stage: verification of onboard N&V and URN

At this final phase of the project, a set of measurements is performed to validate and verify that contract requirements and those stated the Classification Society have been successfully met. The sea trials usually include onboard vibrations and noise, but barely airborne radiated noise measurements neither URN measurements (unless it is eventually incorporated in the vessel specification), because there is no compulsory regulation in this regard.

From the authors' point of view, these measurements, especially URN measurements, might set a performance baseline of the vessel, which can be used for future condition monitoring of the vessel, helping to ship operators to find any anomaly or malfunction in the vessel.

In parallel, these sea trials are also an extraordinary opportunity to perform additional measurements for R&D purposed or improvement of future vessels designs and shipbuilding.

VI. Conclusions

This paper has considered the different aspects concerning to the issue of URN produced by the Shipping sector and how it might be addressed for new vessel constructions as well as for existing vessels through a forecasting of the possible future situation for shipowners and ship operators in the case that an URN regulatory framework is released in the forthcoming years.

On the basis of the topics addressed in the paper, the following main conclusions may be drawn:

- Nowadays, there is no limiting standard for URN emission and unfortunately, being an environmental impact unknown by the general society, since almost all efforts and attention in the prevention of pollution are focused on greenhouse gas emissions. This lack of a specific worldwide regulatory framework and harmonized thresholds of URN produces confusion in designers, shipbuilders and end-users. Here lies the true importance of Canada's actions as an agitator in IMO, R&D and commercial projects performed during the last years in this regard, as well as the fostering of this topic in scientific conferences, engineering fora and maritime sector conferences. It is good to know that this issue is increasingly consolidated in the minds of marine stakeholders.

- Consequently, it has been identified a need of agreement of URN thresholds among biologist community in order to have a starting point for the regulatory bodies.
- In parallel, it is necessary to reach trade-offs between biologists and maritime engineering stakeholders regarding these URN thresholds, in order to set them according to the technical feasibility and the state of the art of the technology.
- Likewise, increasing the URN database of civil vessels and improving the knowledge regarding this phenomenon is essential for developing advances in the underwater noise signature reduction of vessels.
- The comparison of URN signatures should be among vessels of the same type, because is strongly dependent on it. Thus, authors recommend to keep it in mind and define URN thresholds according to the type of vessel and the range of frequencies of impact to marine fauna.
- A harmonization of URN measurement procedures as well as URN data postprocessing should be addressed in order to be able to obtain similar results for a specific vessel regardless the standard use.
- Through the proposal of a URN ID for the worldwide fleet and its inclusion on AIS, could it be possible to compare and control the global impact of URN on the oceans.
- N&V-CM methodology is a validated approach which has been implemented for several projects of research vessels. Following that methodology, it is possible to reach high standards of quality and fulfill with low URN, by means of the inclusion of N&V reduction philosophy in all phases of the project.

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