A quick and technically and economically feasible response on reducing the Underwater Radiated Noise (URN) by existing ships: Control of propeller cavitation and URN simultaneously

Publio Beltrán Palomo (1, Eric Baudin (2, Luis A. Piqueras (3, M. Antonia Tesorero (4,

Richard García Méndez (5, Santiago Molins (6.

1) Técnicas y Servicios de Ingeniería S.L. General Director,

2) Bureau Veritas Solutions M&O. Innovation & Energy Transition Manager

3) 4) Técnicas y Servicios de Ingeniería S.L. Production Department,

5) Técnicas y Servicios de Ingeniería S.L. Developments,

6) Técnicas y Servicios de Ingeniería S.L. RDI Department Manager

RESUMEN

La Organización Marítima Internacional (OMI) ha revisado recientemente las Directrices para la reducción del ruido radiado al agua (URN) procedente del transporte marítimo para reducir el impacto adverso en la vida marina (Ref. MEPC.1/Circ.906).

En buques, la propulsión es la principal fuente de URN, y la cavitación de la hélice, al producirse, es la contribución dominante.

Por el momento, los armadores siguen adaptándose a los requisitos relacionados con las emisiones de GEI (EEDI/EEXI, CII, Fit for 55), reducir URN no puede ser óbice para ello. Además, para buques existentes, la implementación de tecnologías relacionadas con URN aún está en sus inicios.

Se ha desarrollado un enfoque único para permitir a los armadores gestionar sus principales fuentes de URN y la eficiencia de propulsión mediante una solución de monitorización a bordo en tiempo real, digitalmente avanzada y fácilmente adaptable, el Ni-CDS.

Después de realizar una caracterización adecuada del URN, la solución proporciona informes sobre el URN real y, gracias a un análisis intermedio, apoya el mantenimiento de la hélice.

Además, el uso del Ni-CDS facilita la evaluación de nuevos e innovadores activos de reducción de ruido que se están desarrollando en el mercado, pudiendo evaluar la reducción antes y después de su despliegue.

ABSTRACT

The International Maritime Organization (IMO) has recently reviewed the Guidelines for the reduction of underwater radiated noise from shipping to address adverse impact on marine life (Ref MEPC.1 / Circ.906).

From the ship angle, the propulsion is the primary source of URN. The propeller cavitation itself, when occurring, is known to be the dominant contribution of URN.

As per now, shipowners are still struggling to fulfil the GHG emissions related requirements (EEDI/EEXI, CII, Fit for 55). The need for URN reduction cannot be detrimental to GHG emissions. Furthermore, for existing ships, implementing URN-related technologies is still at an early stage.

A unique approach was developed to enable shipowners to manage their main URN sources and propulsion efficiency status by means of an onboard real-time, digitally advanced, and easily adaptable monitoring solution, the Ni-CDS.

After conducting a proper characterization of the ship's URN (onboard/outboard), the permanently installed solution provides a reporting interface on the actual URN and, thanks to a mid-term analysis, advises on the propeller's maintenance.

Moreover, using the Ni-CDS facilitates the assessment of new, innovative, noise signature reduction assets being developed in the market, being able to evaluate the reduction before and after the deployment of the asset.

1. INTRODUCTION

Underwater radiated noise (URN) has arisen as an issue of major concern for the naval industry since the International Maritime Organization (IMO) started working on understanding its consequences to the marine life and identifying what is needed to characterise, to control and to mitigate it, towards the publication of successive sets of voluntary guidelines for URN reduction.

In this article, the context and regulatory framework is first introduced and explained from a historical point of view from its origin until the present situation.

Also, the naval sector is considering URN as a need-to-manage aspect on the operational activities of the ships, so an analysis of the sector needs is presented. Maintenance and efficiency issues are described and taken into account for being the basis of positive reasons to consider URN mitigation measures.

Afterwards, an overview of the importance of the Underwater Radiated Noise is presented. Both the definition and an up-to-date state of the art are described in order to provide a comprehensive scenario, highlighting the technical and scientific point of view in the first place.

Next, the scenario of technical responses to reduction of URN as exposed in the previous paragraph is presented. This scenario leads to the description of a non-intrusive cavitation detection system that achieves excellent results in its task of detecting cavitation of the propeller and advising on the need of taking operational, real-time measures to avoid cavitation thus reducing the URN emission of the ship.

The final section of this article shows examples on the benefits of using a cavitation detection system combined with transfer function approach for URN mitigation. Two case studies are presented and the results are described in detail for guidance on how such a system can be implemented, with low cost, for controlling the main URN source, cavitation.

2. CONTEXT, REGULATORY FRAMEWORK

Back to the 17th century the concept of “freedom of the seas” was in force. The national rights were limited to an area offshore the coastline of the nation of 3 nautical miles. Beyond this limit, the waters are considered international: free to all nations, but belonging to none of them, as stated in the “mare liberum” principle. Closer to our time, several nations pushed, during the 20th century, to reconsider these limits in order to include mineral resources, to protect fish stocks, and to provide the means to enforce pollution controls. On December 10th 1982, was signed in Montego Bay, the United Nations Convention on the Law of the Sea (UNCLOS), also called the Law of the Sea Convention or the Law of the Sea Treaty. UNCLOS came into force in 1994. This international agreement establishes a legal framework for all marine and maritime activities. Nonetheless, no clear mention of the underwater radiated noise from shipping issue was addressed.

In the 1970’s, the United States' Marine Mammal Protection Act (MMPA) of 1972 and the International Convention for the Prevention of Pollution of the Sea by Oil (MARPOL) of 1973 were issued. These regulations focused on reducing oil spills and other forms of pollution that could harm marine life, but they did not specifically address underwater noise.

In the 1980s, concerns about the impact of underwater noise on marine life began to grow, particularly with regards to sonar and other military applications. The United States Navy began implementing measures to reduce the impact of its sonar systems on marine mammals, and international organisations such as the International Whaling Commission (IWC) and the International Maritime Organization (IMO) started discussing ways to address the issue. Australia opened the floor in 1998 for considering guidelines.

In the early 2000s, there was a growing awareness of the impact of underwater noise on marine life. This led to increased research into ways to reduce underwater noise emissions from these vessels, as well as increased pressure on governments and international organisations to introduce stricter regulations. In response to these growing concerns about underwater noise pollution, several international organisations launched initiatives aimed at reducing its impact on marine life.

In 2008, the European Union adopted the Marine Strategy Framework Directive (MSFD). This Directive has derived into national laws from 2008 onwards (e.g. in 2010 in France). At this present day, it remains the first and only legislation to specifically address the underwater radiated noise from shipping and to consider it as a pollution to be evaluated and mitigated. The dedicated Descriptor 11 has been set in view of maintaining levels of underwater noise that do not adversely affect marine ecosystems. Quantifying the thresholds that would be associated with the 'Good Environmental Status' (GES) for underwater noise has triggered a concerted research effort across Europe, alongside dedicated research projects to build-up supporting methodologies and tools. However, the initial objective of achieving the GES by 2020 remains challenged as the clarification expected on the way to quantify more precisely the Descriptor 11 was brought in late 2023.

In the early 2010's the European Commission funded several research projects (BESST, SILENV, AQUO, SONIC) that specifically addressed this issue. As per today two key EC funded research projects (PIAQUO and SATURN) are carrying out various tasks on the different aspects of the problems both with regards to the source of noise (the ship) and to the fauna impacted (invertebrates, fishes, mammals). Within these projects or alongside all the other projects and initiatives the studies have shown that underwater-radiated noise from commercial ships may have both short and long-term negative consequences on marine life, especially marine mammals.

In January 2019, a technical workshop titled "Quieting Ships to Protect the Marine Environment" was held at the IMO headquarters in London. Participants from around the world discussed measures to mitigate underwater noise from ships. Capitalising on this work and on a global acknowledgment that the issue deserved a revision of the existing guidelines, Canada has driven the discussions and efforts at IMO towards this revision. In January 2023, during the 9th session of the Ship Design Committee (SDC9), the IMO members completed the revision of the 2014 guidelines which were further approved by the Marine Environment Protection Committee (MEPC) in July 2023 [1].

Later in 2023, one has to note that an agreement was reached on a High Seas Treaty to be added as an instrument of the UNCLOS convention, to protect ocean life in international waters. This would provide measures including Marine Protected Areas and environmental impact assessments. That said, the International Maritime Organization does play a role, however, as well as other bodies such as the International Whaling Commission and the International Seabed Authority (ISA), which was established by the UNCLOS convention itself.

Lastly, in January 2024, the 10th session of the IMO Ship Design Committee (SDC10) has clarified the scope and key areas of the Underwater Radiated Noise Management Plan and its related Experience Building Phase (EBP) which initial length is set to three years. In brief, the approach proposed relies on the following steps depending on the entity addressed for its consideration:

- baselining (a ship, a fleet when a shipowner is addressed; an area when member States are addressed),
- setting targets,
- listing, evaluating, prioritising the various solutions and corresponding scenarios (e.g. technical/design solutions, operational mitigation measures and all the combinations),
- running the scenarios, implementing the solutions, and
- monitoring the efficiency of it on URN in view of continuous improvement.

3. SECTOR NEEDS

Within the noise radiated by ships, in addition to that produced by machinery, cavitation is recognized as the major contributor of noise radiated into the water. This phenomenon occurs on the propellers of the various ships due to the large pressure gradients that occur between the blade faces of these elements. These phenomena, in combination with the other sources of noise have a series of adverse effects, both on the ship itself and on the environment:

- Erosions on the blades of the propellers produced by cavitation, with the consequent economic cost, time of barge and economic losses due to stoppages, forcing the sector to pay special attention to the propellers of the ships that present this phenomenon.
- Damage to biodiversity, interfering in the population of different marine species, such as cetaceans, causing them to move away from areas of passage of ships, or limiting their ability to communicate, forage and reproduce. This is why, as shown in the previous chapter with the different regulatory frameworks, many countries and ports are moving towards noise control policies, forcing the industry to start adapting to these new trends, or limiting the transit areas.
- Military vessels are particularly interested in controlling their acoustic signature, and therefore their radiated noise levels into the water, as it directly affects their detectability by opposing powers, as well as their ability to satisfactorily perform their mission.

- In the field of recreational ships, similar to military vessels, although with different motivations, the URN levels and cavitation phenomenon is sought to be as controlled as possible, not only to avoid limitations with respect to navigation areas, but also seeking maximum comfort on board.
- In addition, cavitation involves the expenditure of energy to vaporise the water in the areas surrounding the blades, which results in a detriment to propulsive efficiency. This means that the ship has to use more fuel to move at the same speed, implying not only an additional economic cost, but also an increase in the emission of greenhouse gases (GHGs).

First of all, the sector has solutions focused on the design phase of ships that have not yet been built, with design methods and calculation rules that serve as a guide for the design of thrusters without cavitation, or cavitation contained within acceptable values. Among these methods we can find the following main ones:

- Burill's method: which focuses on an increase in the area of the blades to distribute more effectively the pressure gradients that occur in these elements, without having an adverse effect on propulsive performance.
- Keller's method: similar to the previous one, but proposing a formulation to define the developed area/disc area ratios, taking into account parameters such as the number of blades, number of thrusters installed, type of ship under study, etc…
- Numerical methods that, in conjunction with tests on test channels that support their results, allow a detailed design of the thrusters.

Also, to this day, several technical solutions have been considered and, for a few of them, already proven beneficial for underwater noise in new ships. It should be noted that, on the one hand, any solution aiming at reducing ship URN mustn't be detrimental to ship efficiency and so for the related gas emissions.

However, these methods are applicable in the case of vessels that are in the design phase, and the need remains for an effective method to control cavitation and its large contribution to radiated noise to the water.

As can be seen, all maritime sectors are in need of controlling their noise levels radiated into the water, and consequently, the occurrence of the cavitation phenomenon.

While it can be said that at the design stage this aspect is sufficiently covered, with sufficient means to make an adequate design to avoid high levels of cavitation and noise emissions of other sources, and consequently noise radiated into the water, for built ships only considerably limited control methods are available.

Therefore, in order to be able to undertake and adapt to the needs of the sector, as well as to the developing regulations, two aspects are essentially needed:

- Technologies and equipment that allow a continuous monitoring of the cavitation phenomenon, as well as other sources of noise on board, which is also easy and quick to install (to avoid long periods of barging or adaptation of ships, with their consequent economic costs and operating losses).
- Methods to reliably estimate the ship's URN levels in a fast and efficient way, as well as its trend along the ship-life due the different operational conditions.

As a result, the ongoing monitoring of cavitation and URN appears to be a goal-based solution that enables to get a clear picture of the main source of URN as well as to identify any potential increase in unplanned and unwanted loss of energy and so decrease of efficiency and increase of URN.

4. An overview of the Underwater Radiated Noise (URN) importance

4.1. Definition

The Underwater Radiated Noise (URN) produced by ships or their Acoustic Signature is the vibrational energy transmitted by the ship to the water due to the structural noise sources located inside. The main components of the radiated energy, summarised in **Figure 4.1**, are the noise generated by the propeller, the hydrodynamic noise, the vibration induced by the water flow, the vibrations on the hull, and the noise radiated by the machinery on board. Likewise, some sources of hydrodynamic noise are present, which appear by direct contact of the hull with the water: the rotational speed of the shaft, the number of propeller blades, turbulence, cavitation, and sources of methodological noise, such as the level of noise contributed by rain due to the impact of the drops in contact with a surface. This vibration is quite representative and can be detected even at considerable distances (above 10 km) by using sensors installed in submarines and ships.

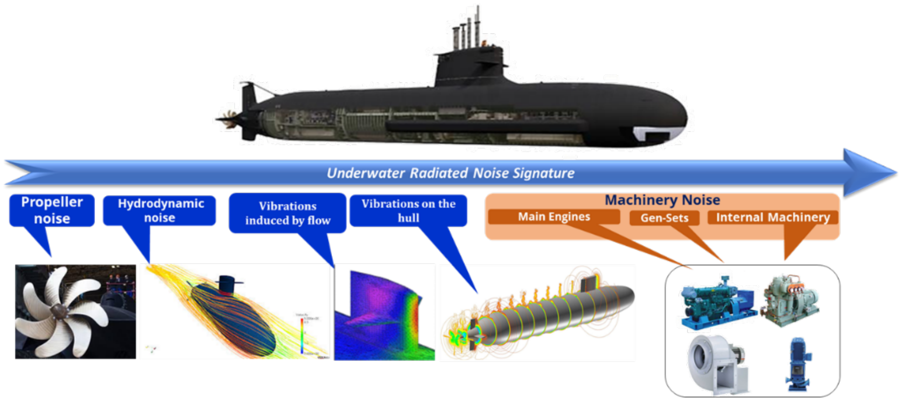


Figure 4.1. URN sources

Based on investigations performed by the Biological and Scientific Communities, shipping has been recognised and accepted by all the Marine Organizations as the root cause of the noise increase in oceans during the last decades as well as its direct impact on marine fauna. Thus, and additionally to the pressure for decarbonization, the marine sector must face this new and unknown “hiding enemy”. Consequently, the reduction of the URN combined with the GHGs, not only for the new ships but also, and particularly, for the existing ones, became the most recent and biggest challenge for the marine sector.

In this concern, it is highlighted that the importance of the URN depends on the type of ships. Thus, for warships and submarines, the URN is directly related to their strategic values, stealth, survival, quality indicators, competitiveness, comfort, less weight and less emissions. For other segments of special ships, like rescue submarine ships, fishing research vessels (FRV), etc., the URN has a close relationship with the performance of their electronic equipment and echosounders, efficiency of the missions, as well as their comfort, weight and emissions. Finally, for the civilian ships, including merchants, yachts and pleasure boats, the control and reduction of the URN become a clear indicator, not just of sustainability, quality and competitiveness, but also an indicator of comfort and less weight with its intrinsic advantages.

4.2. Reduction of URN. The most current “State-of-the-Art”

Since 2008, IMO-International Maritime Organization- through its Marine Environment Protection Committee- MEPC- has released different revisions of the “Guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life (the Guidelines)”. This has been done with the special dedication of different countries, among which are the Flags of Canada, France and Spain and deserve a special mention for their proactive participation. Recently, after the corresponding process of approval, on 22nd August 2023, IMO has published the “Revised guidelines for the reduction of underwater radiated noise from shipping to address adverse impacts on marine life (Revised Guidelines)”. These revised guidelines, applicable to all types of ships, took effect on 1st October 2023 [1].

Having in mind the awareness related to the URN by shipping, IMO invited to all the Member States to use the aforementioned Revised Guidelines with the aim of reducing radiated noise from ships and to bring them to the attention of all parties concerned, in particular ship and equipment designers, shipbuilders, shipowners and operators, classification societies, suppliers, manufacturers and other stakeholders.

The authors, based on their own experience, fully agree with the main pillars that support the strategy defined by the IMO on reducing the URN by ships. Namely, the design stage; the baselining of URN measurements (predicted or actual), understood as the expected URN reference level of the ship as a source derived from prediction (calculations) or experimental measurements; the clear definition of targets for the expected URN and the application, control and assessment of the countermeasures applied to achieve such targets. In this concern, the suitable balance between the reduction of URN and the GHGs shall be considered.

In order to answer the request from the IMO-MEPC, the authors, committed with this strategy, and as specialised designer in the dynamic and acoustical design of silent ships want to share along this paper their practical experiences and observation gathered as results of the application of a dedicated methodology, which have been developed by them on the basis of four decades expertise in the field, and focused on reducing noise and vibration aboard as well as URN by ships. This methodology, named “Noise & Vibration Comprehensive Management" (N&VCM) is applied since the earliest stage of the project (preliminary design) and purchasing stage (control of noise and vibration sources) until the construction period (noise and vibration prediction calculation) and the sea trials that enable us to validate the countermeasures applied to achieve the N&V and URN targets contractually defined. It consists in the application of all the preventive N&V and URN control techniques along with the extension of the project. In summary, as it can be noticed, this methodology encompasses most of the “pillars” of the aforementioned strategy requested by IMO on reducing noise, vibrations and URN on ships.

Based on such wide experience, the practical contributions of the authors could be summarised as follows:

- For new vessels, when the owners intend to obtain, for strategic reasons, improvements in the performance of electronic equipment, or sustainability requirements; the objectives are usually met. In this process are essential the following aspects: *a)* provide the appropriate contractual specification that include not only the related targets of noise, vibration and URN, but also the description of the suitable methodology to follow up by the selected shipyard. *b)* the selected shipyard must be committed with the targets of the project and shall be assisted by a skilled and independent noise & vibration consultant to apply the methodology required. *c)* the machinery and propeller selected must be well oriented to the targets of the project and the corresponding suppliers must be committed too with the target of the project submitting the suitable information related to the dynamic and acoustical characterization of their supplies as N&V and URN sources. The absence of this relevant information becomes a risk not only for the shipyards but also for the owners.
- The use of the prediction tools recommended by the “Revised Guidelines” of IMO in the Appendix 2.” Types of computational models for optimizing ship design and technical underwater radiated noise reduction approaches” [1], and particularly the Finite Element Analysis (FEA), Boundary Element Method (BEM) and the Statistical Energy analysis (SEA) that have been used by the authors along their professional life have been proven to be very efficient to predict, with enough approach, the dynamic and acoustical behaviour of the ships in term not only of noise and vibration on board, but also related to the noise radiated by the ships to the water (URN).

To support these experiences, in **Figure 4.2** the typical models used by the authors in these types of approaches are presented.

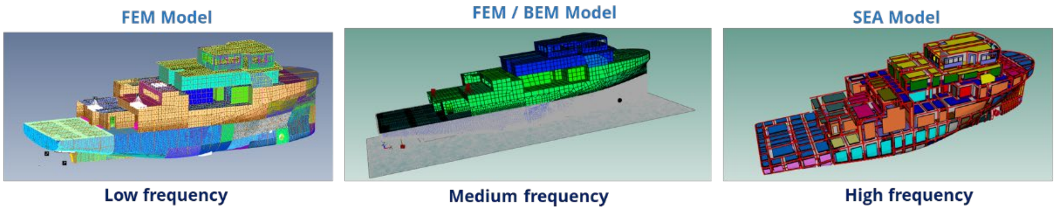


Figure 4.2. Prediction tools used.

Finally, in order to validate the technical consistency not only of these prediction tools used but also the suitability and solvency of the methodology of the *"Noise & Vibration Comprehensive Management"* (N&VCM) applied by the authors to predict the URN of some special ships, in **Figure 4.3** the comparison between the results obtained analytically and the experimental ones obtained by standardized measurement procedure is presented.

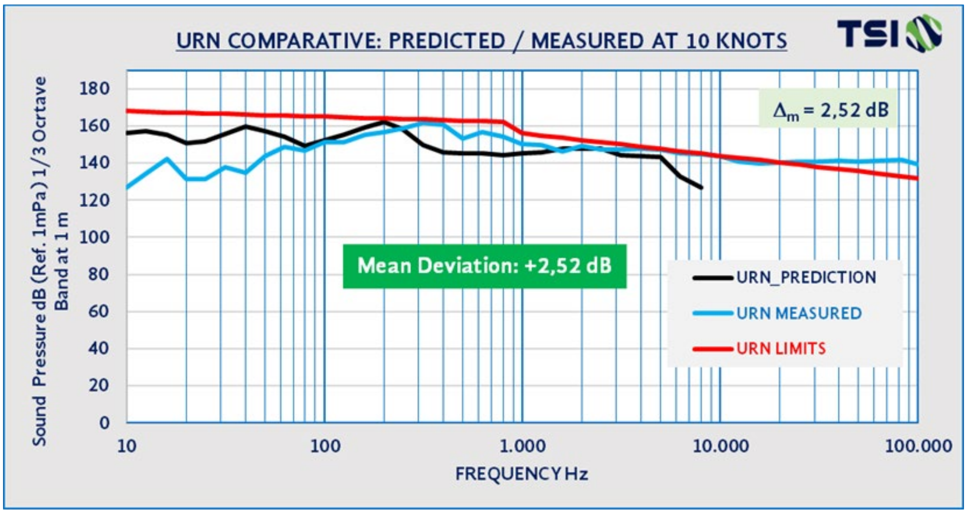


Figure 4.3. Comparative URN Predicted / Measured by standardized method.

As it can be noticed, the results obtained in this representative example, between many other performed by the authors, show a mean deviation of +2,5 dB between the URN predicted for a new ship and the URN measured by a standardized measurement procedure for some defined operational condition, using the prediction tools recommended by the "Revised Guidelines" of IMO [1]. This means a definitive validation not only of the calculation tools available according to the current *"state-of- the art",* but also of the methodology (N&VCM) applied by the authors to reduce the URN of the ships in order to achieve some URN target limits contractually predefined by the owners.

Additionally, it is important to emphasize that having in mind that the compliance with the URN targets contractually required means the application of different preventive control techniques, not only aimed to the main URN sources, but also to the design of the ship, the previous comparison between the results obtained by calculations (prediction) and the experimental ones enable, additionally, the assessment of the effectiveness of the different solutions applied as well as their potential absence of impact in other aspects such as energy efficiency, emissions and ship safety.

- It could be concluded, as the authors have been doing in different publications [2],[3],[4],[5],[6] that the Maritime Sector currently has, not only URN prediction tools sufficiently validated experimentally, but also a wide range of technical solutions to reduce and control underwater radiated noise by newly built vessels. The majority of these technical solutions do not have significant impact on the GHGs. Consequently, its application, mandatory or not, remains on the shipowners' side and/or the competent Regulatory Bodies.
- In this context, it is important to emphasise that the accuracy of the URN prediction by calculation is fully conditioned by the capability of the suppliers of the main URN sources to provide the dynamic and acoustical characterization of these supplies. It must be noticed that the absence of this information could have a direct impact in the achievement of the URN targets, the costs, and the weight of the ships and, consequently, in the GHGs. From the authors point of view, concise recommendations related to this aspect should be considered by IMO to be included in the new guidelines.
- Finally, it is also noteworthy that both the prediction tools and the methodology mentioned above for the reduction of URN are extensible to the retrofit processes of existing ships for those shipowners who decide to reduce the noise radiated by their ships. In these cases, an evaluation of the technical and economic feasibility of the possible corrective actions to be applied is mandatory.

5. PROPOSAL OF QUICK AND TECHNICALLY FEASIBLE RESPONSE ON REDUCING THE URN

5.1. Introduction

According to UNCTAD STAT 2022 [7] there are currently and approximately 102.899 ships around the world involved in the shipping. Its distribution is the following: Oil tankers: 11,565; Bulk carriers:12,714; General cargo: 20,112; Container ships: 5,589 and other types of ships: 52,919. Based on the same source, as of 2022, the average age of all ships in the world merchant fleet was just over 20 years. General cargo ships were the oldest type of vessels, with an average age of around 27 years. Some 68 percent of the world's cargo ships were older than 15 years, in contrast with about 21 percent of bulk carriers. Based on the previous data, the current status of this fleet in term of its URN could be summarised as follows:

- It is expected that most of them have been designed prioritising the aspects of performance without other environmental considerations. Consequently, it is also expected that their propellers have been designed to achieve the maximum performance and, so, with high risk of cavitation at some operational conditions. A quick exam of the available URN databases provided by MF McKenna [8], PT Arveson and DJ Vendittis [9], Eric Baudin [10], confirms the aforementioned assumption related to the cavitation of the propulsion system of these ships.
- Due to their age, none of these vessels have had any requirement for noise radiated into the water included in their contractual specification; including a high percentage of the most modern. Thus, nothing has been done to limit or reduce the URN of this population of current ships in operation.

Having in mind that the reduction of the URN for new ships, as it has been described in the previous paragraphs, is feasible to be achievable when the owners include this new URN requirement in their contractual specification and when they request to the shipyards the application of prediction tools and methodology already proven, the pending challenge of the Marine Sector related to URN will be to find the quick, practical and economical solutions that enable to reduce or mitigate the URN of the existing fleets.

Nowadays, several technical solutions have been considered and, for a few of them, already proven beneficial for underwater noise. However, any solution aiming at reducing ship URN mustn't be detrimental to ship efficiency and so for the related gas emissions. This is also valid for any operational mitigation measure which mustn't lead the shipowner to deteriorate the vessel's CII.

Among the various sources of noise that radiates around the ship, the propeller's cavitation is likely to be the most energetic and spread over a large frequency band. That said, propeller designers are easily defining geometries that avoid full sheet cavitation (extended on a significant part of the blade) but it appears to be a bigger challenge to avoid totally tip vortex cavitation. Moreover, the optimization of propellers with a primary objective of efficiency shows that it becomes a trade-off to simultaneously optimise the propeller URN by reducing the cavitation. And this optimization is valid for one (or a limited range of) given operating condition (driven mainly by the considered ship's speed).

Furthermore, alongside ship's life, the fouling on the hull and on the propeller are not only incurring losses of efficiency but are likely to significantly increase propeller cavitation.

Complementary, the "Revised Guidelines" of IMO [1], include a detailed summary of design, technical, operational and maintenance URN reduction approaches applicable to new and/or existing ships as far as practicable. At the moment, the authors are unaware of shipowners´ feedback related to the implementation of these recommendations. However, everything seems to indicate that, due to the massive nature of some of these recommendations, most of them are waiting for the experiences of the most pioneers.

In this concern, in the next paragraphs the authors, based on their wide experience over 40 years in this field, present their proposals of response on reducing or mitigating the URN of the existing ships. As will be seen, these proposals are fully aligned with most of the recommendations detailed in the "Revised Guidelines" of IMO [1]. These proposals have been designed with the two following criteria:

- Its implementation shall be not intrusive and with null technical impact in the existing ships.
- Cost-effective solutions.
- Quick to be implemented, and
- Both proposals could work alone or combined.

5.2. Response 1. Control and ongoing monitoring of propeller cavitation.

Among the various sources of noise that radiates around the ship, the propeller's cavitation is likely to be the most energetic and spread over a large frequency band. In fact, IMO definitively recognizes that *"...once cavitation occurs, it is typically the most dominant noise source*" [1]. As a result, the monitoring and control of cavitation appears to be a goal-based solution that enables to get a clear picture of the main source of URN as well as to identify any potential increase in unplanned and unwanted loss of energy and so decrease of efficiency and increase of URN.

By other hand, with the development of the different Guidelines and regulations that is being carried out, in the not-too-distant future, ships will have to have a high level of knowledge of when and how their propellants cavitate, in order, in those navigation areas where it is necessary, adapt to the limitations related to the URN that are established.

The authors with the gathered experience acquired through their participation in the EU projects BESST, SILENV, AQUO and the current one SATURN, all of the focused on mitigating the URN, have developed the "No-intrusive Cavitation Detection System - Ni-CDS". Ni-CDS comprises a non-intrusive cavitation monitoring system which autonomously detects the existence of cavitation phenomenon by monitoring the vibration transmitted to the hull. By the use of the algorithm patented by the authors, cavitation is determined in terms of both occurrence and intensity [11].

The primary aim of this novelty system in relation with the reduction of the URN of the ships is the accuracy identification, in real-time and for the real operational conditions of each ship, of the presence and intensity of the propeller cavitation for such operational conditions. Once the crew is informed, in real time, of the presence of this phenomenon, they will be in a position to apply the operational corrections that correspond to its mitigation and, consequently, the elimination of the largest contributor to the noise radiated into the water by the ship.

The Ni-CDS, **Figure 5.1**, is made of hardware components that collect and record various metrics including but not limited to vibrations, RPM, blade pitch, rudder angle, and ship speed. Likewise, the system has been designed to incorporate static parameters such as emissions, consumption, geolocation, etc. These measurements are processed by Ni-CDS' patented algorithm for analysis and cavitation monitoring. These records and analysis enable the user not only to monitor the status propellers cavitation but also to avoid the operational conditions that cause undesirable cavitation levels and so, high levels of URN.

Figure 5.1. Ni-CDS system and graphical user interface.

The installation process of the Ni-CDS is non–intrusive and can be installed quickly onboard. This means that no great efforts must be performed to implement the system on board: no hull penetrations or holes of any type, and no drydock services are required.

The mandatory sensors are a tachometer and two or three accelerometers. The accelerometers to control the structure borne noise induced by cavitation are installed at internal points of the ship's structure, which are studied based on their position and rigidity characteristics, with no need to install anything outside the hull and without the need to modify it, **Figure 5.2**. Additionally, its calibration can be performed by non-expert personnel. Ni CDS system calibration is performed by increasing the RPM during the start-up of the propulsion system and processing the vibration data for different ship drafts. Once calibration has been performed, the system is capable of estimating the cavitation intensity in terms of percentage.

Figure 5.2. Accelerometers installed inside the ship, on the structure.

For operation, after calibration, the system can be run at any time or in continuous mode. During execution the system provides the ship's crew with real time information about the existence and intensity of cavitation. This information can help the captain make decisions to avoid cavitation phenomenon or reduce its intensity.

Historical data is also stored for future analysis. Raw and processed data could be explored later to study the evolution of the ship's cavitation conditions. This can also be useful for optimising the calibration parameters.

Related to ship parameters or conditions, the Ni-CDS system can collect and register several parameters for monitoring the ship operation and cavitation phenomenon. For this purpose, it is provided with analog and digital interfaces (inputs) that can be easily configured to gather data from the available ship's interfaces. Analog inputs comprise analog channels for voltage signals. The digital interface is Modbus TCP. By means of the enabled interfaces the system can collect and store any signal available from the ship that can be useful for analysing the cavitation conditions.

The Ni-CDS system provides several indicators of the vessel conditions and cavitation status in real time, **Figure 5.3.** They include trend graphs and cavitation maps that show the evolution of the cavitation phenomenon versus the main vessel conditions.

Figure 5.3. Interface Ni-CDS system.

It is also possible to view raw data like time signals, FFT and spectrograms in real time. These can be useful for analysing the current conditions and confirming the cavitation occurrence. The system can also provide alarms and computed values as analog outputs that make it possible to integrate cavitation information into any external or vessel systems.

Finally, the Ni-CDS has been validated through the experiences in real cases of ships with severe indications of propeller cavitation as well as by means a complementary verification at CEHIPAR in their cavitation tunnel**. Figure 5.4** shows some data obtained in this measure.

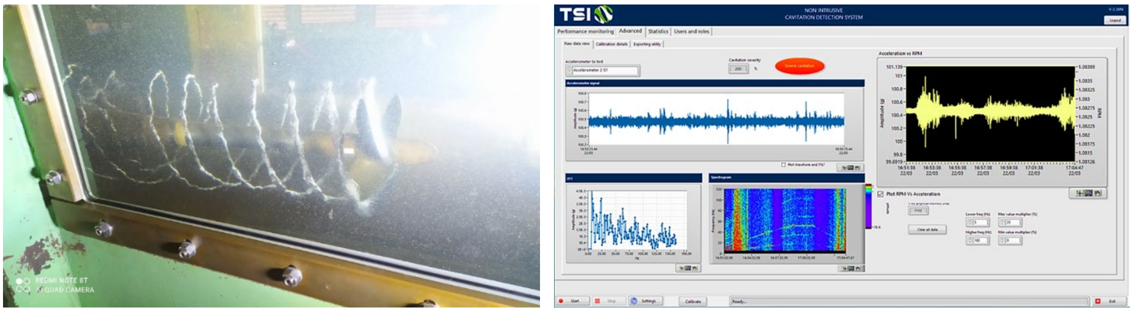


Figure 5.4. Results of validation of Ni-CDS at cavitation tunnel.

While the non-cavitating and efficient propeller is invented or other major modifications are implemented that demonstrate its efficiency in reducing URN, an easy, fast and response/solution is presented by the authors that allows controlling in cost-efficiency way the cavitation of the propellers as the main and recognized cause of the high URN of ships as well as the control of the operational parameter that enable to avoid this undesirable phenomenon.

5.3. Response 2. Ongoing monitoring of URN of existing ships.

According to the "Revised Guidelines" of IMO, the ongoing monitoring of the URN is considered an essential step toward assessing the reduction of noise in oceans. This activity could be done through the measurements of the actual ship URN, as starting point of the URN Management Planning, recommended by the guidelines, or by the modelling of ship URN based on its characteristics and design parameters, as well as environmental conditions.

Having in mind this requirement and considering that the starting point of it is the baseline of URN (as a reference) that, according with the current standardised measurement procedures must be done under sea calm state conditions, the key question is "How to know the URN of the ship along its life or when it being in operating at other operational conditions different at which the URN measurement has been performed?

To provide a response/solution to this new challenge of Marine Sector, in the next paragraphs the authors details two cost-effective methodologies based on real cases that combining the proposal of control of cavitation, detailed previously, would enable to estimate and control the URN of any existing ship in real time and for any operational conditions.

5.3.1. Case Study 1

Within the EU "Saturn" project for the corresponding comparison / harmonisation, URN measurements have been performed in a ship and according to all the standardised measurement's procedures in deep and shallow waters and with different deployment of the handling buoy of the hydrophones. **Figure 5.5.**

Figure 5.5. URN measurements.

In parallel, during the URN the system Ni-CDS was deployed in order to simultaneously measure acceleration at different locations of the hull and rpm of the propulsion system. In **Figure 5.6** the arrangement of this instrumentation is presented.

Figure 5.6. Ni-CDS instrumentation.

In **Figure 5.7** the summary of the results obtained during the measurement campaign are presented in terms of URN expressed in dB (ref. 1Pa) sound pressure in 1/3 octave bands at 1 m of the hull at different operational speeds and the and the corresponding acceleration at the locations of the hull at the same conditions.

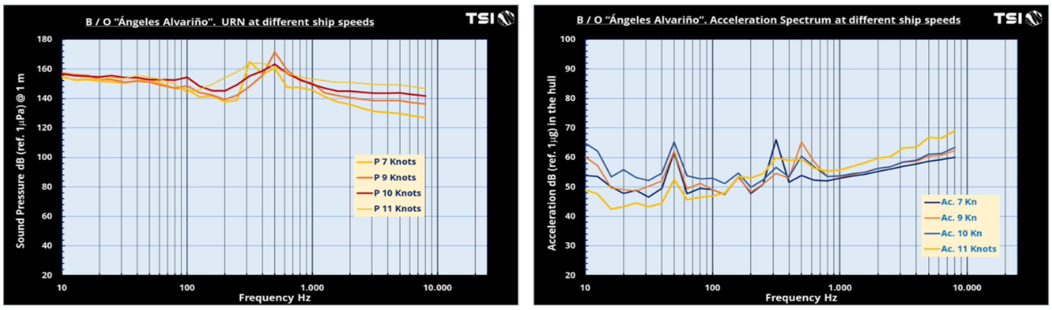


Figure 5.7. Experimental results: Hydrophones and Ni-CDS instrumentation.

As a theoretical approach, the authors have used the method of the Transfer function shown in **Figure 5.8.** The transfer function (TF) is defined as the relationship between the input and output of a linear system in the frequency domain. Knowing its analytical expression will allow us to obtain the output that is produced in the system due to a known input.

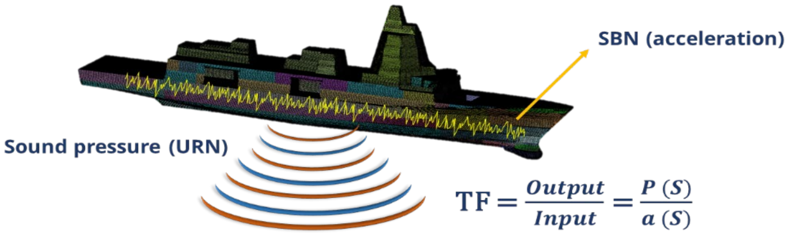


Figure 5.8. Transfer Function formulation.

The acoustic signature of the ship, in terms of sound pressure P(S) radiated by the ship-system, is the output or response of said system to the accelerations (inputs), in terms of structural noise (SBN), induced in the hull. by the machinery and other components of its propulsion.

Once the Transfer Function of the system is known, we will be able, by measuring accelerations in the hull in different conditions, to estimate and know “in real time” the acoustic signature of the ship in those conditions.

Based on the experimental results obtained during the measurements and the theoretical approach applied, in the attached **Figure 5.9** is presented the weighted Transfer Function obtained for this ship.

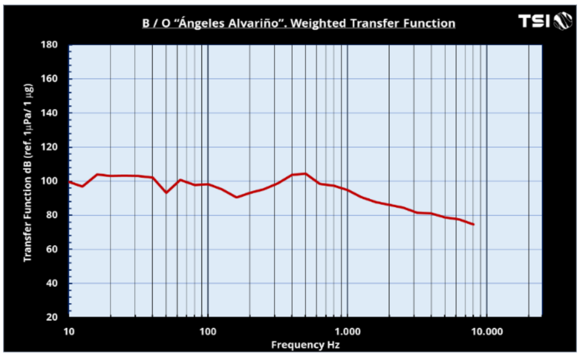


Figure 5.9. Transfer Function for the ship.

To validate the analysis performed, in the attached **Figure 5.10** are presented the comparative analysis between the URN experimentally measured by standardised measurement procedures at different operational speeds of the ships and the corresponding URN estimated by the methodology applied.

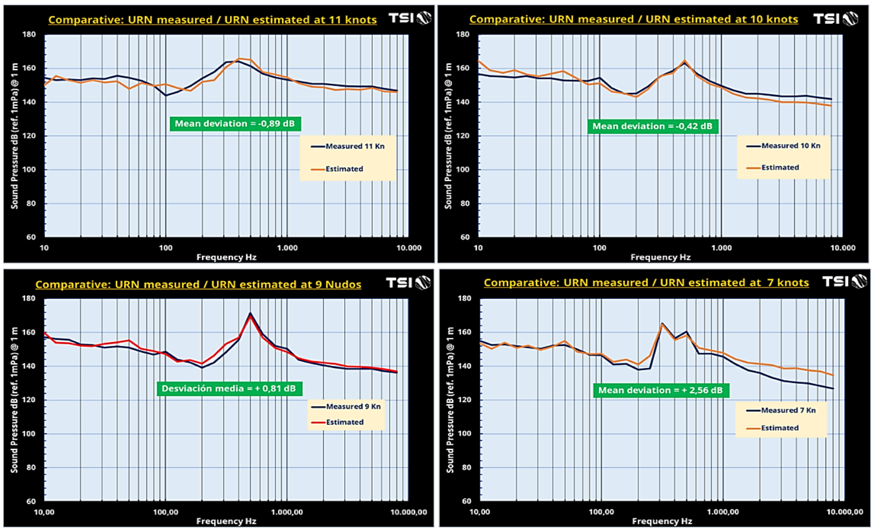


Figure 5.10. Comparative: URN measured / URN estimated.

As it can be seen, the deviation between the experimental results and the estimated one's present mean deviations that vary between -0,8 to +2,6 dB.

Furthermore, because this response/solution includes the use of the Ni-CDS system, the ship's crew has not only real-time information on the ships URN, with sufficient approach, but also and simultaneously ongoing information on the intensity of cavitation in the propellers of the propulsion system at each operational condition, **Figure 5.11**.

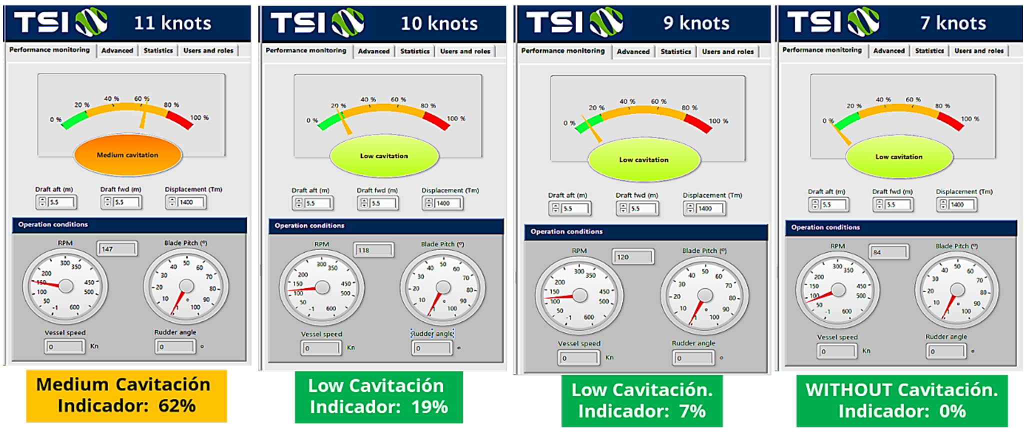


Figure 5.11. Cavitation level indications.

5.3.2. Case Study 2

In this second case, the measurement carried out is the typical static URN test. As its name indicates, with the ship moored to the dock, different equipment considered as main sources of URN are started consecutively and measurements of vibrations or structural noise are carried out in the feet of said equipment simultaneously with the noise radiated to the water by installing a hydrophone on the side of the vessel at a distance of 1 m and placed as close as possible to the source to be analysed, such as schematically is shown in the **Figure 5.12**.

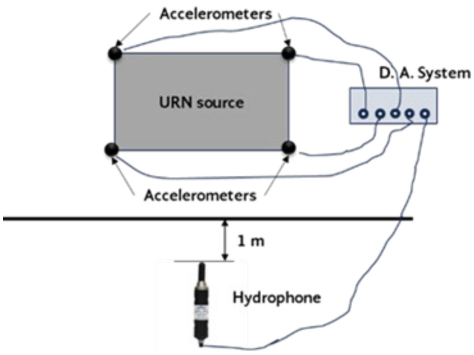


Figure 5.12. URN static measurement.

Using the same theoretical approach of the transfer function described in the previous paragraphs, and based on the structure borne noise measured at the foundations of each unit in operation and the sound pressure levels obtained through the hydrophone located at 1m of the hull side as close as possible of each source, the transfer function (TF_i) for each URN i-source has been obtained. **Figure 5.13**.

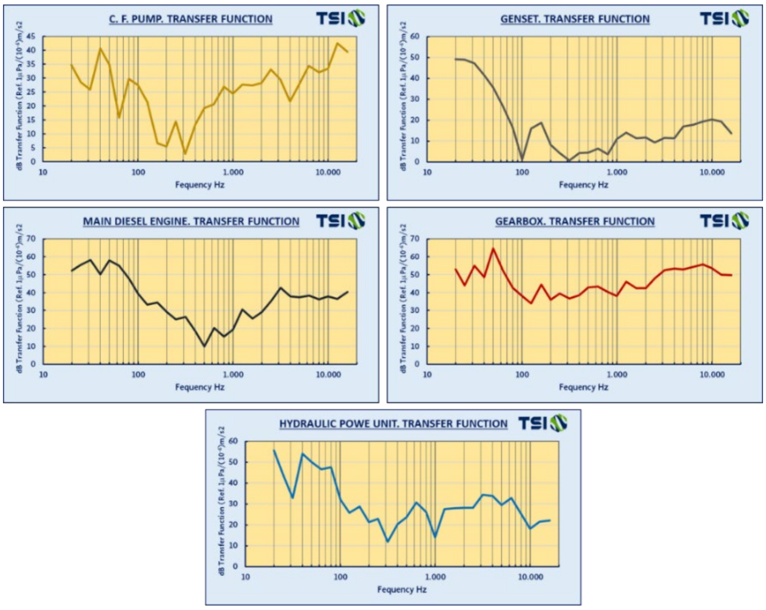
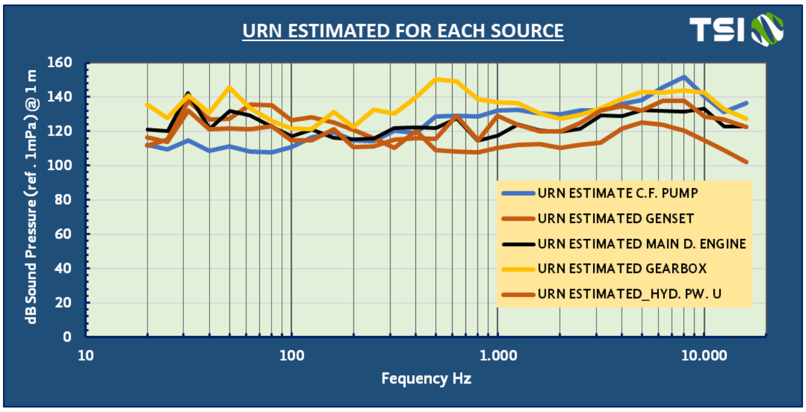
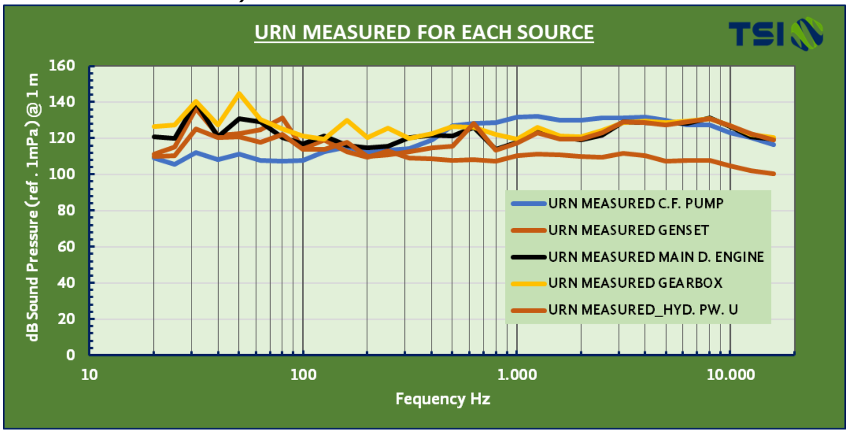


Figure 5.13. Transfer Functions of the different URN sources

Operating the TF of each URN source with the structure borne noise (SBN) measured at each of them through the vibration measurement performed on board, is obtained the estimated URN for each URN source tested. In the attached **Figure 5.14** are presented, for each URN source, the URN value estimated analytically through the TF a), and the experimental ones b) measured with the hydrophone at 1m of the hull side.



a) URN estimated for each source



b) URN measured experimentally for each source

Figure 5.14. Comparison URN estimated / measured for each URN source

The comparison between the URN estimated and the experimentally measured for each URN source enable to highlight the following aspects: a) the mean deviation for each URN source varies between -1,1 (for the main diesel engine) to 8,6 dB (for the case of the gearbox), of the estimated value in relationship to the measured one; b) the estimation or approach could be considered conservative due that the estimated values are always lightly over the measured ones.

Finally, in the assumption that all the URN sources considered in this approach are operating simultaneously, in the attached **Figure 5.15** are presented the URN measured (sound pressure level obtaining combining the experimental results obtained from the hydrophone located at 1m) in comparison with the URN estimated as result of the combination of the URN estimated of each one of the sources considered individually.

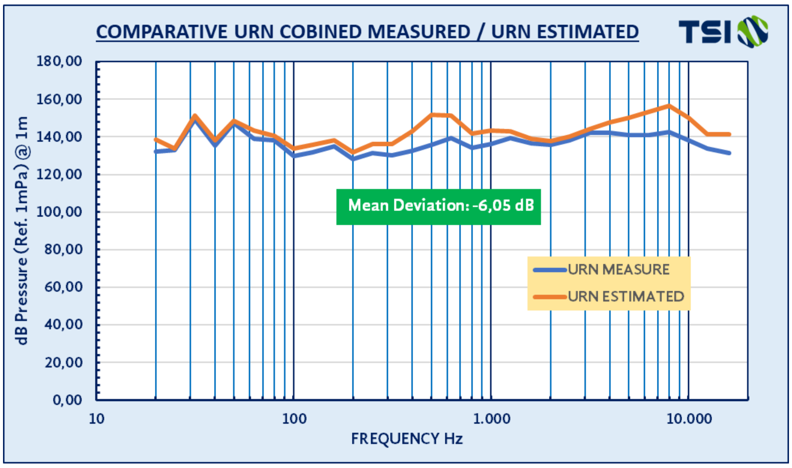


Figure 5.15. Transfer Functions of the different URN sources

As it can be seen, the mean deviation obtained with this approach achieves a value of -6 dB and, same as it was aforementioned, the URN estimate is also conservative, being the estimated value slightly over the experimental one.

5.4. Summary of Results: An approach to the URN digital twin of the ship

In order to answer the recent requirements of the IMO´s “Revised Guidelines” [1] aimed on reducing the URN of all type of ships: new building and, particularly, the existing ones, through this paper the authors have presented a battery of responses/solutions with the purpose to contribute, as noise & vibration consultants) and as it is required by IMO to all the shareholder involved, to achieve the current great challenge of the Marine Sector as it is the mitigation, in the far quick, economical and technically feasible, of the major contributor of the increase of noise on the oceans. Following there is a summary, among others, of the main advantages of the authors’ responses/solutions proposed:

1) For new building ships, the Owner´s contractual requirement of some URN target included in the specification of the new ships is the “sine qua non” and definitive condition to achieve the target of reduction/mitigation of the URN of such ships. In those cases, as it has been proved not only for special ships but also for all types of ships, the Marine Sector has tested and validated prediction tools, technology and methodologies, which allows it to provide a satisfactory response to these environmental requirements of URN reduction. And all of it, at a reasonable cost, crew-comfort additional advantages and without harmful effects in terms of energy efficiency and emissions. Consequently, the mandatory character of the URN target definition by Owners could be a significant and essential step in the strategy of URN reductions.

2) Other, and far more complex of how it is looking, is the technological strategy to be applied for the existing ships focused on reducing their URN. This complexity is explained, among others, for the wide reasons explained previously: mean age of the current fleet, their propulsion system has been, mostly, designed under the premise of maximum performance and, so, with propellers very loaded with high risk of cavitation; and finally, that all of these ships have been built without any type of URN or environmental requirements.

3) Last but not least, it must be considered that currently the shipowners are submitted to a growing political, media and regulatory pressure to decarbonize their ships. If to this we must add new regulation on a new matter as the URN, unknown by the majority of them and not considered as directly related with the exploitation of their ships, from authors ‘point of view, the involvement of the shipowners in this second aspect could be consider as not priority and, so, fail. A confirmation of this concern, could be the low proactivity of the shipowners when implanting the wide variety of URN reduction approach suggested by the IMO´s "revised guidelines" that include, among others, hull design modifications, propeller design and modifications, wake flow improvement, machinery design and modification, etc; in summary, modifications with significant economic impact and, at the moment, uncertainty related to their efficiency.

4) In this complex scenario, the authors, as it has been detailed in the previous description of their responses in the above paragraphs, they have opted for solutions that are characterised by:

a) To encompass two of the essential pillars or aspect focused on reducing the URN of the ships:
- Control and ongoing monitoring of propeller cavitation, undesirable phenomenon identified as the major contributor of the URN of the existing ships.
- Ongoing monitoring of URN of existing ships, that starting from the URN base line of the ships will assess and validate the potential improvement solutions gradually applied as well as the potential improvements in terms of maintenance and operational conditions.

b) The responses/solutions proposed are:
- Quicks and very easy to be implemented on board the ships in operation, without any modification or interferences on their operations. In no case are dry-dock services required.
- With low economic impact in comparison with other approaches. The potential impact will be related with dedicated sea trials focused on getting the URN and the vibrations measurements at the main URN sources.
- Based on the URN baseline of the ship, able to provide information to the crew in real-time of the changes in the URN along the ship-life and due to its different operational conditions.

5) Finally, the implementation of these type of solutions would enable to incorporate the control of the URN and the control of the propeller cavitation, as sustainability indicators, in the expected digital twin models of the ships.

6. Conclusion

In this article a complete view of the underwater radiated noise by ships issue regarding the maritime industry has been presented. From the described increasing interest in understanding, monitoring, controlling and mitigating URN, a movement towards developing effective, low-cost solutions has been ongoing during recent years. One of the main agents for this is IMO, who is pushing the sector towards URN control and mitigation as the recently published guidelines are enforcing the recommendations in order to include URN among the factors to be considered both for new ships and also for retrofitting existing ones.

As shown in previous paragraphs, it can be concluded that there exists a complete set of technical solutions at the design phase that can be efficiently applied to control and mitigate URN on newly designed and built ships. Although these solutions are proven and validated experimentally for URN reduction, they don't have a significant impact on GHG emissions and as such remain voluntary. The good news is that an increasing number of new contracts for ship building include URN requirements.

From section 5, where a proposal for a quick and technically feasible response on reducing the URN is presented, it can be concluded that there exists a solution for achieving an efficient and low-cost implementation of a system for producing a URN estimation of the ship. It is achieved by monitoring the vibrations induced by the main identified noise sources, including but not only, the cavitation occurrence, which is the main URN source when it happens. The system employs onboard vibration measurements and advanced mathematical approaches to assess the URN transfer function of the different sources, producing a real-time indication of the estimated URN level of the ship. This level can be used for taking the appropriate operational measures to reduce URN at any time. This demonstrates that not only new vessels but also existing ones can benefit from effective, low-cost solutions for URN reduction as being increasingly demanded by the sector.

7. References

[1] MEPC.1/Circ.906. 22 August 2023. Revised Guidelines for the Reduction of Underwater Radiated Noise from shipping to address adverse impacts on marine life.

[2] Publio Beltrán. (2008). Ingeniería Naval. *Buque Oceanográfico Miguel Oliver: La excelencia en ruido y vibraciones a bordo cumpliendo ICES nº109.*

[3] Publio Beltran, María Antonia Tesorero (2010). Ingeniería Naval. *La Construcción Naval Española preparada para responder a los nuevos y exigentes requerimientos medioambientales. Nuevos retos y oportunidades.*

[4] Publio Beltrán. et al. (2012). ECUA. *Achievement of the new URN requirements*.

[5] Publio Beltrán. *Why Should Fishing Research Vessels (FRV) Be Certified? Their Technological Role in the Current Challenge to Reduce the Underwater Signature of Commercial and Navy Ships*. CIDIN 2019, COPINAVAL 2019: Proceeding of the VI International Ship Design & Naval Engineering Congress (CIDIN) and XXVI Pan-American Congress of Naval Engineering, Maritime Transportation and Port Engineering (COPINAVAL).

[6] Publio Beltran. *Shipbuilding and new requirements to reduce the environmental impact of ships. New technological challenges and business opportunities. 2012.* Ship Science & Technology.

[7] UNCTAD Handbook of Statistics 2022.

[8] MF. McKenna, D. Ross, et al, *Underwater radiated noise from modern commercial ships.*

[9] PT Arveson, DJ Vendittis. *Radiated noise characteristics of a modern cargo ship.*

[10] Eric Baudin, C. Audoly, T Gaggero. Mitigation of underwater radiated noise related to shipping and its impact on marine life: A practical approach developed in the scope of AQUO project.

[11]. Publio Beltran. L. Piqueras, Richard Garcia. *Sistema No-Intrusivo de Detección de Cavitación, una herramienta para mitigar el ruido en los océanos y proteger la fauna marina.* 61 Congreso de Ingeniería Naval.