Annex 3

Inventory of measures to mitigate anthropogenic underwater noise

– Shipping –

Report No. M173483/03

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Table of contents

1 Introduction

The present report on noise mitigation measures for underwater radiated noise (URN) from shipping addresses different technical and operational measures against the background of the status of international goals for the reduction of URN, and with the aim of providing recommendations for the strategic and target oriented planning and selection of such measures for an efficient reduction of URN. This report focusses on the efficiency of design and technology approaches to optimize URN reduction. Aspects of energy efficiency (EE) and greenhouse gases (GHG) are considered. The basic strategy is to control the dominant sources of noise and to describe specific reduction measures for new builds, retrofits and operational concepts to reduce the noise input into the sea.

Chapter 2 deals with the noise sources from different ship types and depicts their contribution to the overall URN of a ship. A ranking of noise contributors - (cavitating) propeller, structure-borne noise, … - is presented based on examples. To reach a high efficiency in the reduction, these main contributors need to be addressed first.

Chapter 3 discusses the URN goals, whereby minimum goal must be not to worsen the URN and ideally to achieve a "good" acoustic situation.

Chapter 4 and Chapter 5 shortly discuss relevant measures – constructural/design and operational measures – referring to listings of URN mitigation measures. Again, focus is put on the main contributors depicted in Chapter 2.

Chapter 6 refers to the monitoring of URN outlining the necessity of quality assurance of the applied measures and the URN footprint of a ship.

Appendix A presents the answers of a questionnaire on noise URN measures, which had been distributed to relevant stakeholders (consultants for ship, offshore and underwater acoustics, experts from research institutes (e.g. model basin, technical departments, propeller design), industry experts (e.g. manufacturer of engines) and representatives from public authorities) in the context of this report.

Key messages

Key messages are outlined along the report in these kinds of boxes.

A considerable amount of very valuable work on reducing underwater noise caused by shipping operations has already been carried out and published. Among others we want to especially highlight the following:

- IMO, MEPC.1/Circ.906 - Revised guidelines for the reduction of underwater noise from shipping to address adverse impacts on marine life [33],
- the AQUO project (Achieve QUieter Oceans by shipping noise footprint reduction technical reports and guidelines ([2], [3], [4]),
- the VARD reports ([27], [29]) with the extensive list on mitigation measures,
- EMSA Sounds: Status of underwater noise from shipping report [11],
- from Sweden and Belgium:
  Underwater noise from fairways – policies, incentives and measures to reduce the environmental impact [16],
  Reduction of emissions and underwater radiated noise for the Belgian shipping sector [17],

and of course

- all the precious reports related to the ECHO project of the Port of Vancouver ([5], [6], [12], [18], [19], [21], etc.).

These contributions towards a reduction of underwater noise have provided a very useful input/basis for the present report.

2 Noise sources and ship types

2.1 Noise sources and levels

The underwater radiated noise (URN) of a ship depends on various sound radiation paths, also called transfer path (TP), see Figure 1. Each transfer path starts with one or more noise sources which directly (e.g. propeller noise or flow noise) or indirectly (e.g. machinery vibration trough ship structure) contribute to the overall underwater radiated noise. The most relevant sound radiation paths are:

- TP 1 - Propeller sound: propeller noise and cavitation,
- TP 2 - Structure-borne sound (SBS): machinery noise vibration through structure into shell plate vibrations,
- TP 3 - Airborne sound (ABS): machinery noise air noise through structure into shell plate vibrations,
- TP 4 - Fluid sound: noise through openings, and
- TP 5 - Flow noise: flow-induced noise from flow over hull, appendages, and openings.

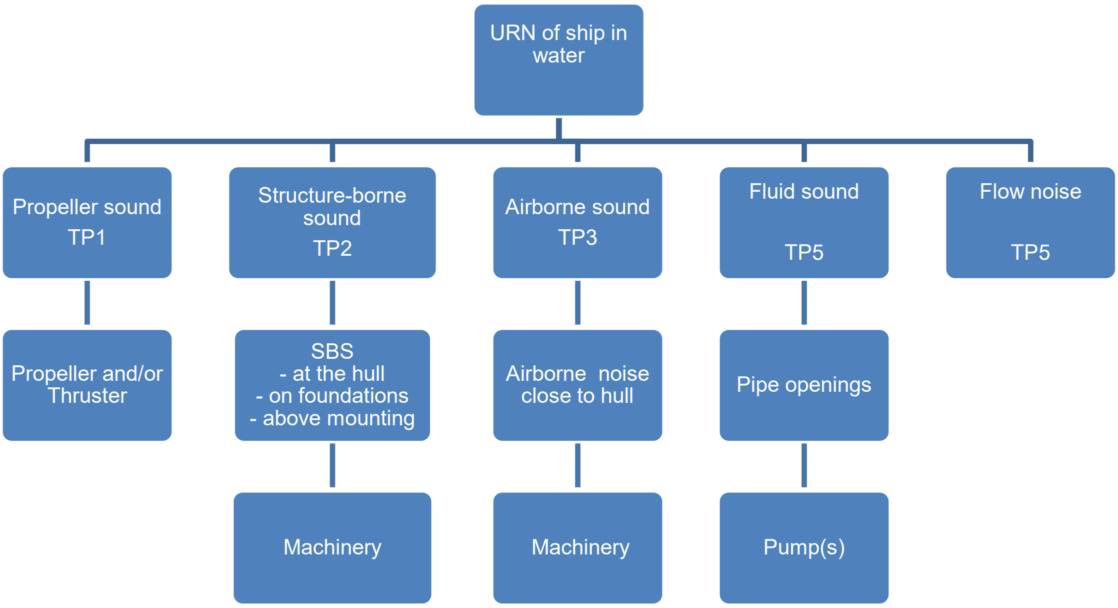

Figure 1: Underwater radiated noise of a ship in water (TP: Transfer Path).

Each of the transfer paths contributes to the overall underwater radiated noise, whereby the underwater radiated noise spectrum is dominated by highest transfer path levels at a specific frequency. Hence to achieve an effective reduction of the underwater radiated noise of a ship the transfer path with the highest levels at a specific frequency needs to be addressed first.

Figure 2 (upper row) shows different transfer path contributions (propeller sound, structure-borne sound, and three issues representing other transfer paths) and the resulting underwater radiated noise. Additional to the initial state, two mitigation variants are illustrated (Figure 2 middle and lower row). The mitigation of the propeller results in a reduced overall underwater radiated noise. The mitigation of the machinery in the second variant has no relevant effect on the overall URN since the propeller path remains the dominating contribution to the overall URN.

The example strengthens the statement that the dominant path (in the observed condition) needs to be addressed first.

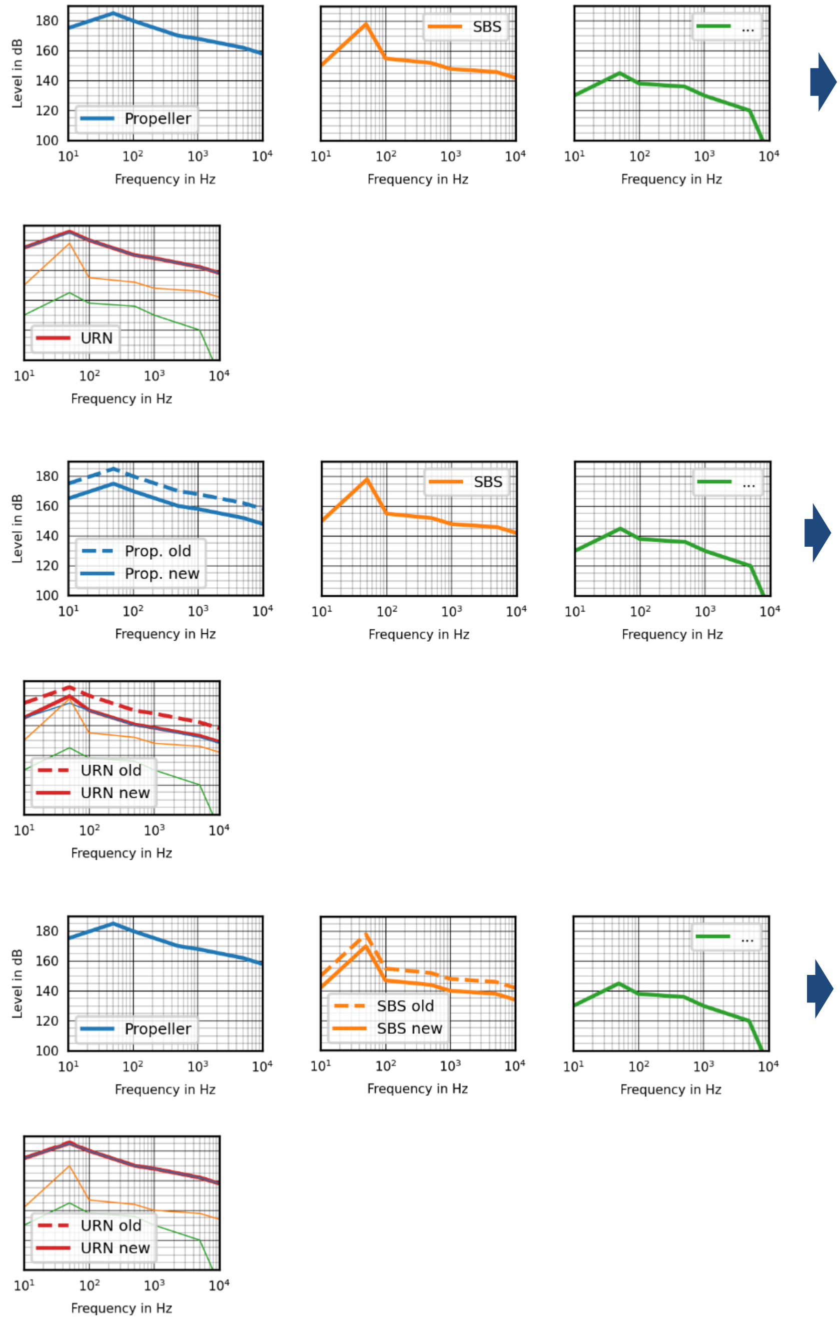

Figure 2 : Contributions (propeller, SBS and other) to overall underwater radiated noise. Top: initial state, middle: improvement of propeller, bottom: improvement of structure-borne noise.

Depending on the (constructural) design (ship structure, propellers and/or thruster, installed machinery, etc) and the respective operational profile of a ship (draught, speed, etc.), one or more sound transmission paths are dominating in the underwater radiated noise. For most of the commercial ships, the main contributors to the URN are the propeller(s), engines, and onboard machinery ([33], [9]). In case cavitation occurs, the propeller is typically the most dominant noise source.

Figure 3 shows frequency ranges where specific ship noise sources have typically their highest levels. Some noise sources are relevant in a small range, others are present in a very wide range and in most ranges, there is an overlap of more than one noise source. Hence to reduce noise levels of a specific frequency range different noise sources with different mitigation measures are necessary.

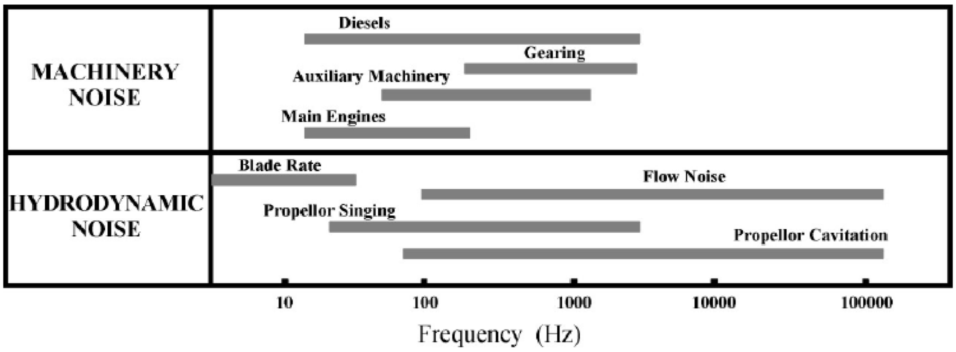

Figure 3: Frequency ranges of ship noise sources (adapted from Norwood in [35])

A qualitative distribution of the dominating contributions to the sound radiation depending on the transit speed is shown in Figure 4. At higher transit speeds, the propeller noise dominates due to the cavitation, which causes a broadband increase of the URN in a wide frequency range, but also leads to an increase in the low-frequency range at the orders and suborders of the propeller blade frequencies. The propeller sound radiation is composed of the fluid-structure interaction and radiation of the propellers, the direct radiation of the cavitation noise and, especially in the frequency range < 100 Hz, the structure-borne sound radiation of the ship's structure excited by the propeller and < 1000 Hz of the propulsion system. At lower speeds the propeller noise contribution decreases and other noise source, gearbox and propulsion system, become dominant in the ship signature.

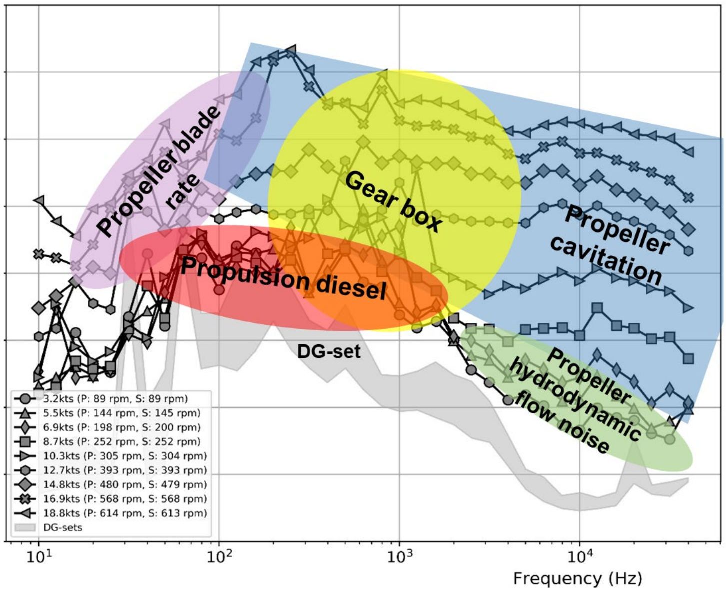

Figure 4: Classification of the main sources contributing to the radiated underwater noise signature of an ORCA-class training vessel (from BURNSi [14])

Another qualitative example of underwater radiated noise levels of a bulk carrier is shown in Figure 5. At the highest ship speed, the underwater radiated noise is dominated in all frequency by propeller cavitation noise. With decreasing speed (reduction of propeller load and therewith cavitation) a tonal tone (around 30 Hz) independent of the ship speed of the diesel generator determines the underwater radiated noise level. The ship speed at which no cavitation is present on the propeller is called cavitation inception speed. The cavitation inception speed is different for every propeller and pitch angle. For specific ship types (e.g. bulker, tanker or container) characteristic average cavitation inception speeds were identified and typically vary between 9 kts – 14 kts.

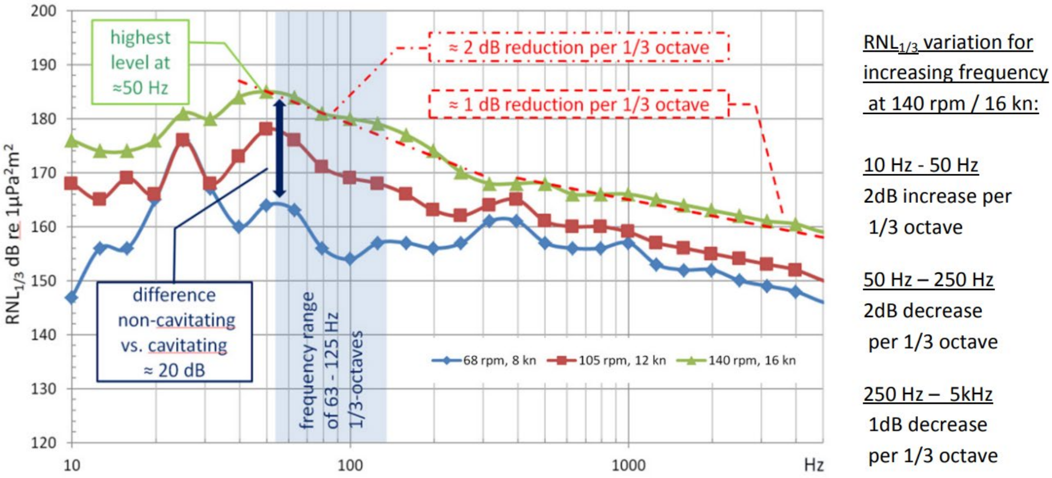

Figure 5: Influence of ship speed on underwater radiated noise of a bulk carrier (from [4] adapted from [9])

The knowledge of URN source level of a ship allows a comparison with typical ambient noise levels in water defined by wind, spray, water depth, etc., often referred as Wenz curves [30]. To assess the effect range of a ship, its source level can be complemented with a propagation loss to assess up to which distance the anthropogenic ship noise exceeds the ambient noise. The computation of the site and situation specific propagation loss is a complex theme (e.g. [12]), however, already simple approaches (log – laws) allow comparative evaluations.

Figure 6 shows a comparison of the URN to be expected in a measurement distance of 100 metres for different ship types (container, tanker, research vessel, submarine) and reference curves (DNV Silent R and Silent E, [32]). The source levels of the ships are extrapolated to the distance of 100 m using a transmission loss calculation based on a 20 · log – law. Due to their operation, the most sophisticated ships/boats (research vessels, submarines) should, in principle (at a certain distance), not be detectable in the presence of any ambient noise. This leads to a high demand for acoustic measures and technical innovations, such as electric propulsion systems with, for example, fuel cells, battery solutions, etc., which are already being used in the planning of special ships today. Quiet ships and research vessels already achieve limit values at 11 kts that are a good 20 dB below the typical sound values of commercial shipping. To achieve these sound values, the propeller must not cavitate or sing. The BSH research vessel is one example for such a silent research vessel with design optimization. In this case, the propeller has been given a damping alloy to reduce sound radiation and avoid singing effects. The drive is diesel-electric with single-stage resilient mounting of the electric motor without gear stage and double resilient mounting of the generators, all relevant auxiliary units are resiliently decoupled. Finally, attached to the graph are typical sound pressure levels of tankers, bulk carriers and container ships from the current global fleet, prognostically determined as a good average estimate using measurement data from the ECHO project [5] and JOMOPANS projects [8], among others, see [18].

Remark:
Contrary to research vessels and submarines with a primary purpose to be quiet, commercial ship's primary purpose is to carry payload with highest possible EE. The payload mainly defines the hull shape, draught and propeller size, and therewith the URN at a given speed.

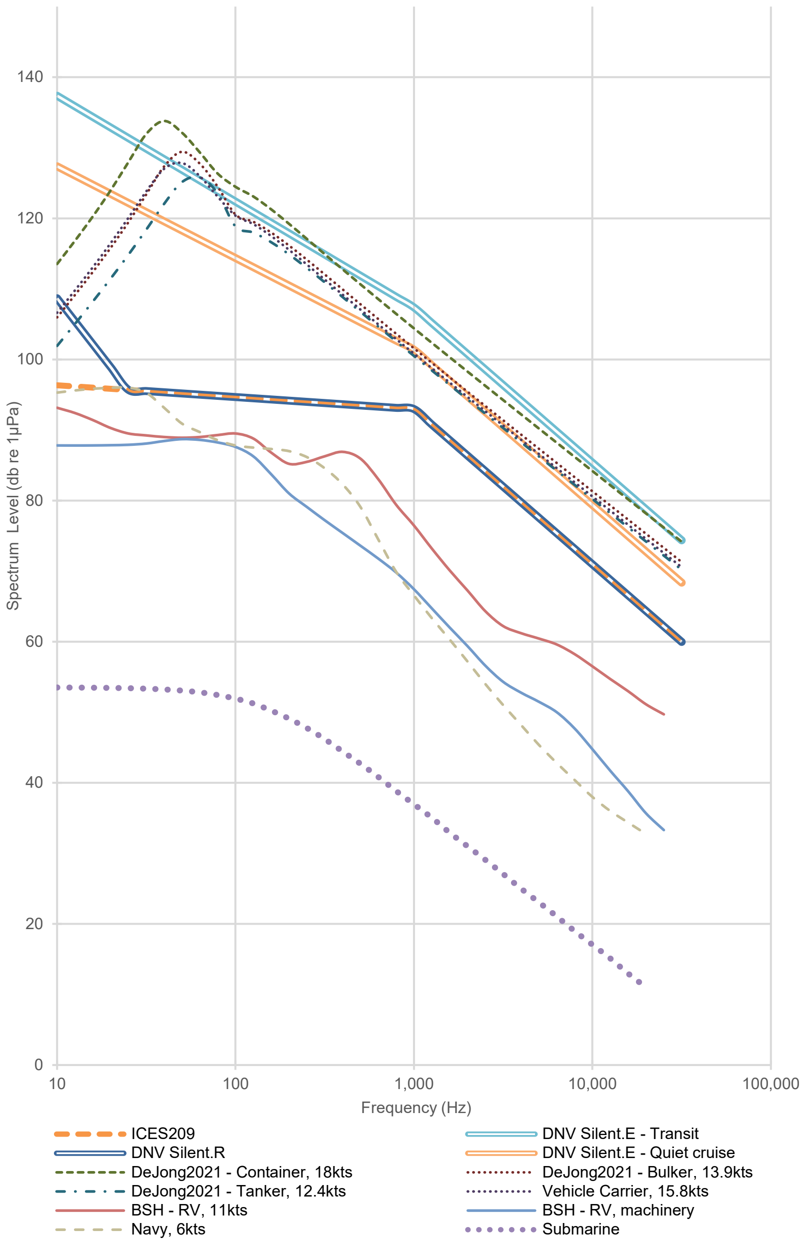

Figure 6: Comparison of the underwater radiated noise levels to be expected in a distance of 100 m for different types of ships (using 20 · log - low).

In summary, noise control concepts depend on the propulsion system, ship type, application (transit, dynamic positioning (DP)) and ship speed. Physical constraints include the cavitation inception speed as well as the weight of machinery (low, medium, high speed), as this means that noise control measures can be implemented with varying effectiveness.

Determination of the loudest contribution to URN

To effectively reduce the URN of a ship it is necessary to understand the different contributions to the URN and in a first step address the highest contributors of each frequency range.

A combination of different mitigation measures addressing different contributors in different frequency ranges might be necessary.

Remark: Chapter 2.1 describes different steps as follows,

- Evaluation of noise sources and URN of a specific ship,
- Comparison of results for selected conditions with URN targets,
- Implementation of effective mitigation measures addressing major URN contributors,
- Monitoring and re-evaluation of URN with respect to URN targets, if necessary, restart,

which are also reflected in the IMO Guidelines, Appendix 3, Sample Template #2 (Plan-Implement-Monitor-Evaluate cycle) as a basis for an URN management plan, see [34].

2.2 Classification of ship types, machinery and propulsion system

As introduced in the prior chapter the main contributors to the URN of a ship are the propeller, main engines and onboard machinery. Thus, these criteria should be considered when defining a classification with regard to underwater radiated noise.

Most of the commercial ships feature one or two propeller shaft systems with fixed propeller(s). Other common systems are shaft systems with variable pitch propeller(s), podded or cycloidal propeller(s). The emitted noise relates to the propeller design (CIS, noise at design speed) and the prevailing loading condition (rpm, torque and thrust coefficients).

Regarding the main engines for large commercial ships two stroke diesel engines with auxiliary four-stroke diesel generator-sets and in certain cases a shaft generator or a gas turbine for electricity generation are state of the art. Smaller ships are mostly equipped with four-stroke diesel engine for propulsion machinery and generator-sets for electricity generation. A third large group are ships equipped with electric engines for propulsion and four-stroke diesel generator-sets. Machinery noise is mainly introduced indirectly via mounting, foundation and ship structure through the ship hull into underwater radiated noise. Thus, URN reduction can be achieved on this propagation path e.g. through optimized mountings and ship structural design.

The type of a ship defines the hull form. For example, while a tanker features a hull form with a large block coefficient with a huge draught, a ferry has a slender hull form with a smaller draught. The hull form and especially the wake field are important design parameters for the propeller and therewith having an indirect influence on the underwater radiated noise.

For different ship types, characteristic ship speeds can be identified: e.g., tankers travel at a rather slow design speed, while container ships are commonly cruising at a higher design speed. The design speed and therewith the design of the propeller has a large influence on the URN. A URN optimized propeller design can lead to a low URN, while a propeller design with no focus to radiated noise may lead to an overall high URN level of a ship. For this reason, predictions only considering the ship speed as parameter and empirical data (and not the propeller design) may lead to misleading decisions regarding URN optimisation.

A more general classification in tabular form was made in the project AQUO and is summarized in Table 1.

Table 1: Classification adapted from AQUO report [2], with additions.

Ship type	Typical engines	Additions
Tankers, bulk carriers and container vessel:	Two stroke diesel engine with auxiliary four-stroke diesel gen-sets and in certain cases a shaft generator or a gas turbine for electricity generation and energy recovery respectively. In addition, steam turbines may be also used to supply cargo pumps.	Mostly operated at two draughts (ballast and design), container ships travelling relatively fast (around 20 kts) compared to tankers and bulkers (10 to 15 kts)
Cargo (RO-RO, RO-PAX, car carriers, general cargo, etc.)	Two stroke diesel engine with auxiliary four-stroke diesel gen-sets and in some cases a shaft generator or a gas turbine for electricity generation and fuel recovery.	One draught, often with controllable pitch propellers and thrusters for manoeuvrability reasons
Ferry and passenger vessels	Four stroke diesel engine for propulsion machinery and gen-sets. Modern ferry vessels generally have installed diesel-electric propulsion due to its manoeuvrability.	One draught, often with controllable pitch propellers and thrusters for manoeuvrability reasons
Cruise ships:	There is a mixture. Modern cruise ships tend to have on-board electric engines for propulsion and four-stroke diesel gen-sets. Within older cruise ships, typically four stroke diesel engines are used for propulsion.	One draught, often equipped with podded drives, propellers in optimized wake field and optimized for low cavitation to guarantee conform on board
LNG	Due to the fact that they carry Liquid Natural Gas inside, they commonly use steam turbines for	Two draughts (ballast and design), mostly equipped with twin shaft

Ship type	Typical engines	Additions
	propulsion and electricity generation. Anyway, a shift to diesel-electric is being seen due to its better efficiency and low operational cost.	system and propeller with relatively low loading
Ships that must use dynamic positioning for their operation (offshore supply vessel, etc)	Ships that must use dynamic positioning for their operations such as drilling vessels, uses diesel-electric propulsion due to its optimal manoeuvring and positioning properties.	One draught, often equipped with ducted propeller for high thrust at low speeds, equipped with thrusters
Fishing vessels:	Four stroke diesel engines for propulsion and electricity generation.	URN in building specification
Research vessels:	Diesel electric propulsion due to their demanding underwater noise requirements.	Optimized URN as building requirement

Figure 7 shows results of an evaluation of the ECHO dataset by vessel category, [21]. The decision of the vessel categories was derived from the predominant ships passing the measuring stations, e.g. explaining the “tug” category. On the one hand the results provide a statistically reliable impression of noise levels from different ships and their variance. Note that depending on the ship type the difference between the loudest and the quietest ship can be up to 30 dB (not knowing if the ships are realistically comparable). And on the other hand, the assessment of the operational parameters (speed draught water and draft from merged vessel noise database) gives a good insight in typical ship speeds and draughts for each category.

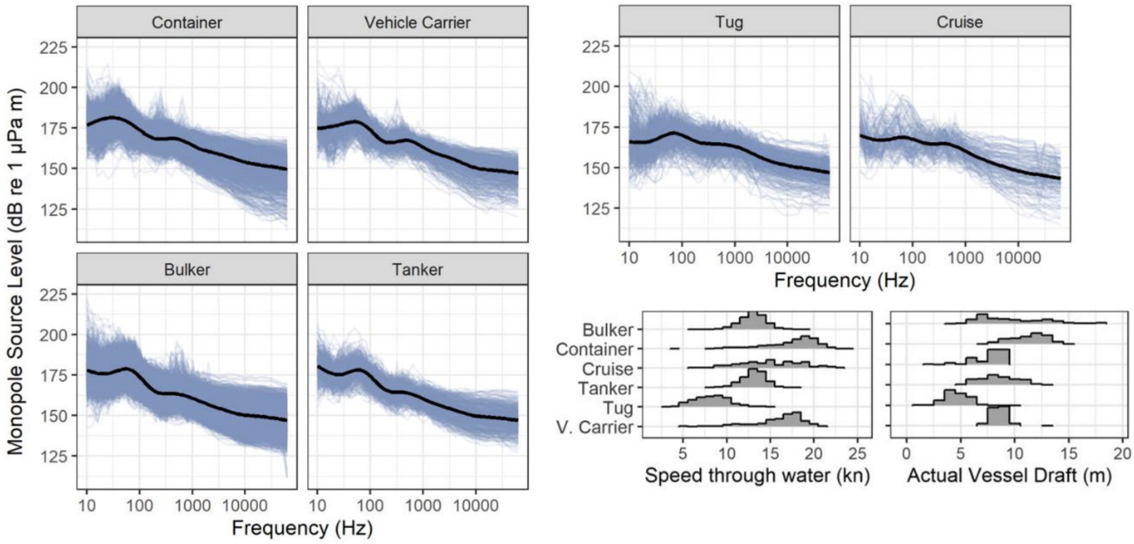

Figure 7: Measurements results and histograms of operational variables from the ECHO dataset by vessel category (adapted from [21])

The large scatter between the different ship types and between ships of the same type suggests that regardless of any classification approach the real URN of a single ship should be evaluated.

3 URN Goals

3.1 Introduction to URN goals

In 2014 IMO released the guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life [33]. The guidelines have been revised and IMO's Marine Environment Protection Committee (MEPC 80) approved the revised guidelines [34] in July 2023. The IMO has included URN goals in its revised guidelines and recommends including such requirements in the context of URN managing planning. Currently, in the guidelines there are no binding requirements for URN of ships.

There are mandatory requirements for GHG, NOx and SOx, EE, PM, (EEDI, EEXI, and CII [37]). GHG, NOx, Sox and PM usually improve with increased EE and thus have an indirect relation to URN. The measures taken to meet these requirements largely affect the URN, as illustrated in Figure 8.

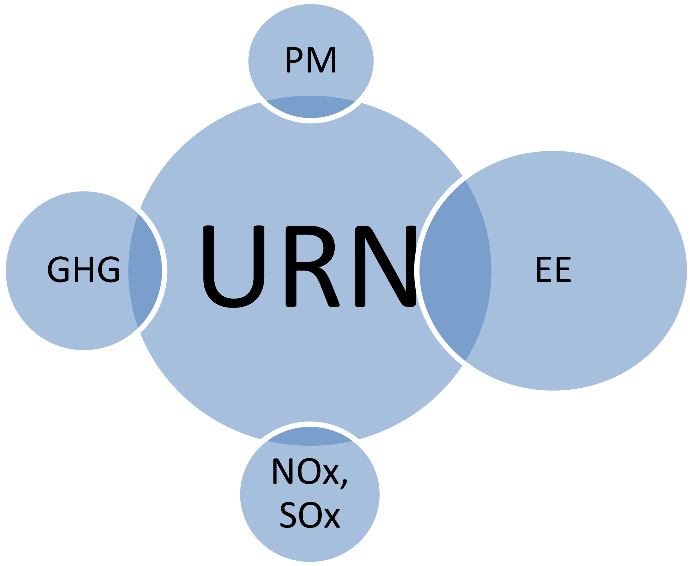

Figure 8: Technical measures to reduce emissions (GHG, etc.), increased energy efficiency that can/will have an impact on the URN.

An IMO Expert Workshop [37] on the relationship between Energy Efficiency (EE) and Underwater Radiated Noise (URN) was held in September 2023. One aim was to discuss the co-benefits between increasing energy efficiency, reducing greenhouse gases and reducing URN, and to discuss various measures such as propeller optimization or energy saving devices. The discussion was based on the Vard reports [27] and [29] in which the mitigation measures were categorized, and co-benefits of measures were named.

For new builds as well as retrofits, measures to comply with the requirements for EE should ideally help to achieve an optimized acoustic situation, intentionally integrating design and technology to reduce underwater radiated noise and GHG emissions at the same time. A minimum objective should be to ensure that such measures do not worsen the URN.

Combine EE and URN goals

For best environmental purpose, EE and URN goals should be considered together.

For new builds as well as retrofits, measures to comply with the requirements for EE should ideally help to achieve an optimized acoustic situation, intentionally integrating design and technology to reduce underwater radiated noise and GHG emissions at the same time. A minimum objective should be to ensure that such measures do not worsen the URN.

3.2 URN goals for ship designers and ship builders (New building, Retrofit)

URN goals can be quantitative targets for the sound emission of a ship, the so-called source level, which ranges spectrally from (1)10 -100000 Hz. Another goal can be the determination of the Cavitation Inception Speed (CIS) for different operating conditions of the ship to have an estimation of the sailing speed without cavitation. To give the ship designer or shipbuilder an orientation, requirements for class notations of classification societies can be used. All classification societies in the world provide such class notations, see the compilation in the IMO Guideline, [33], examples of which are the European class societies BV, DNV, LR and RINA. A small drawback is that these URN requirements are not harmonised and use different acoustic metrics, see e.g. analyses in the framework of the ECHO programme, [9].

As proposed by the IMO guidelines [33] the shipowner should made acoustic specifications for new builds or retrofits of ships. The concepts of the specification could be:

- Prediction of the URN for a given design and comparison with URN goals to determine the status quo or
- URN prediction to optimise the design with regards to URN goals.

In the optimal case, URN limit curves are defined for different speed and loads, e.g.

- Normal transit speed
- Silent transit speed (close to CIS)
- Slow speed (below CIS)

which could be relevant for typical operations. The advantage is the optimised design for different speeds and loads under the aspects of EE, GHG and also URN.

3.3 Verification, certificate and incentive

Ideally, measurements should be carried out to verify the URN. If the specifications for URN are based on the class notations, the underlying measurement methods are applied. For other specifications, ISO 17208-1 [39] ISO17208-2 [40] (deep water) and soon ISO 17208-3 [41] (shallow water) standards can be followed.

To assess the influence of a technical measure on the URN, e.g. when retrofitting ships, the basic condition must be known or at least be assessable. How can this be achieved? The best way is to take measurements on the existing ship and identify the baseline.

URN measurements may be a cost factor that people are generally not prepared to pay without obtaining a benefit. A comparatively inexpensive measurement compared to URN measurements is the onboard measurement, which evaluates a URN equivalent level by means of pressure fluctuation measurements in the stern area of the ship hull above the propeller. Classification societies such as DNV and BV offer this type of measurement. The drawback of this approach is the accuracy of prediction, but on the other hand, they continuously provide URN data compared to single sea trial campaigns.

URN measurements of existing ships or class certificates might help to to classify ships in future. Quiet ships should be supported with incentive measures that could be integrated into an Environmental Shipping Index (ESI), e.g. [7]. Such incentive schemes are already being discussed and implemented nationally, such as in Canada [6].

Definition of future URN limits

In view of future mandatory URN regulations, thresholds shall be developed.

In the meanwhile, incentive measures and regional thresholds should be considered to promote noise reduction.

4 Constructural/design measures

4.1 GHG, EE and URN (constructural/design measures)

As described in chapter 3, mandatory requirements exist for ships with regard to EE and GHG, as well as current non-binding guidelines for the reduction of URN. When considering URN measures for the design and construction of a ship, these need to be in line with the existing mandatory requirements on GHG, EE (and PM, NO_x, So_x) and any interactions of optimization measures between the three aspects must be taken into account, see also [27]. [20] presented a comparison of the predicted URN from model tests between two retrofit propeller designs with (nearly) the same efficiency. While the URN contribution of the propeller 1 exceeds corresponding classification notations the propeller 2 features an URN which could lead to an overall URN of the ship below the notations. The example shows that URN can be fulfilled with no drawbacks on EE criteria.

4.2 Low noise design – propeller, propulsion system

As described in Chapter 2, the propeller, the propulsion system and structure-borne noise are particularly relevant for a low noise design of ships, hence in this report these contributors are mainly addressed.

Major reports addressing URN optimization and mitigation measures are the AQUO report [3] and the VARD reports [27], [29]. While report [3] and [27] focus on listings (with extensive explanation in [3]), the latest VARD report [29] also gives a rating regarding the potential advantages or disadvantages in relation with GHG and EE.

Effectiveness of measures
Many reports provide a tabular listing with measure effectiveness with an expected noise reduction in decibels in the corresponding frequency range where the measures act (e.g. VARD [27] and [29], IMO [36]). The proposed URN reduction approaches may be considered as solution to reduce the URN of ship However, the effectiveness of approaches need to be specifically evaluated for the ship considered.

Examples from the VARD report [27] tabular listing are:

- 2.1.1. Propeller optimization: dB change: depending on the original propeller design, freq. range: -
- 3.2.1. Resilient mounts: dB change: >10 dB, freq. range: all
- 3.2.8. Metallic foam: dB change: unknown, claimed as > 10 dB, freq. range: unknown

The examples refer to three completely different measures. Considering this input only, the choice would fall on measures 3.2.1 and 3.2.8 with dB change larger than 10 dB. However, from an overall URN approach (see Figure 2) the loudest contributor needs to be addressed first to get an effective reduction of the URN of a ship. Thus, a cavitating propeller should always be addressed first. If the propeller noise of a ship is already low, measures on the structure-borne machinery noise (e.g. resilient mounts) are likely to lead to an improvement of the overall URN. The effectiveness of metallic foam on a reduction of the overall URN of a commercial ship is rather questionable.

Recommendations regarding propeller design measures
There are numerous types of propellers: skewed propellers, ducted propellers, CLT propellers, podded drives, etc. State of the art is to choose the type according to the ships purpose. E.g. tugs are often equipped with ducted propellers – for high torque at low speed, container vessel mostly with fixed pitch propellers – for high efficiency at design speed, ferries often with controllable pitch propellers – for good manoeuvrability. In all cases, a propeller featuring a high efficiency and good URN should work in an optimal wake field. The ship hull has to optimized and energy saving devices improving the wake field should be considered. Additionally, to the criteria on efficiency, two URN design criteria should be applied:

- propeller design with high cavitation inception speed (CIS) and
- propeller design with low URN at design speed (conditions).

If propeller singing occurs, it should be prevented by an anti-sing edge.

Recommendations regarding propulsion system measures
The type of propulsion system is the first decision defining the URN contribution from machinery. While very large commercial ships are generally equipped with large 2 stroke engines for efficiency reasons, for other ships (or with another design weightings) there are multiple options to improve URN:

- conventional: 4 stroke engines,
- diesel-electric propulsion (shaft system or podded drives),
- alternative propulsion systems (e.g. gas system, electric only),
- assisting propulsion (e.g. wind).

The current list is focused on propulsion systems and is not dealing with optimization of the drag and therewith leading to less loaded propeller and propulsion system.

Reduction of structure-borne noise
The very large commercial ships are generally equipped with large 2 stroke engines (for efficiency reasons) with no real option for measures. For this type of engine, no resilient mountings exist. They are installed deep in the ship close to the hull and are a relevant source of structure-borne noise. However, their effect on URN is primary in a very low frequency range.

Smaller engines (4 stroke and generator sets) offer the possibility to be resilient mounted. For generator sets a position further away from the hull is yet another option.

A fundamental element in reducing structure-borne sound is a profound design of the ship structure with an appropriate foundation for the engines (e.g. high stiffness, optimized thickness of top plates).

URN in design stage

The URN level of a ship is predefined in early design phase; thus, URN focus needs to be included from an early stage of design phase.

At this stage most measures can easily (with minimal effort) be integrated into the ship leading to an optimized URN, e.g., optimised ship structure, mitigation measures and propeller design with focus on URN.

4.3 Low noise design – additional measures

There are multiple measures, which gain relevance when the main contributors (propeller noise, noise from machinery) have already been addressed. For standard commercial ship these kinds of measures often apply in specific conditions and within a limited time span. Examples are silent running, dynamic positioning in protected areas, harbour approaches.

They can be divided into two main categories:

- measures with a direct influence on the URN, and
- measures with an indirect influence on the URN.

To the first categories refers to measures as:

- air lubrication system,
- damping of tanks.

The measures with an indirect effect cause by their mechanism another contributor to improve its URN behaviour, e.g. drag reduction implies a reduction of the propeller load resulting in a URN reduction of the propeller.

Examples are:

- wind assisted drives,
- fuel cells, batteries,
- energy saving devices (ESD),
- hull form optimization,

leading to less load on the propeller and propulsion and therewith reducing the noise main contributors.

Qualified Judgement of measures effectiveness

The decision on the measures and consequently the corresponding effectiveness needs to be closely matched to the specific ship and should be taken by experts.

5 Operational measures (cavitation control, speed reduction, etc.)

5.1 EE, GHG, URN (Operational measures)

The advantage of most operational measures is that they address EE, GHG and URN in concert. The drawback of the operational measures is, that they only change (e.g. by speed reduction) or restore (e.g. by hull cleaning) the as-built URN and EE status. The EE, GHG and URN baseline of a ship remains at a constant level.

5.2 Speed reduction (rpm reduction)

For ships with a fixed pitch propulsion (FPP) system a speed reduction will also induce a relevant reduction of the underwater radiated noise. Speed and rpm reduction is engaging multiple positives effects:

- reduction of the propeller loading and therewith, very likely if present, reduce the cavitation noise and reduce the propeller pressure pulses,
- reduction of driving power and therewith reducing the structure borne and airborne noise contributions of the machinery,
- reduction of the flow noise which also correlates with speed in water.

For controllable pitch propellers (CPP) there are three options:

1. ship speed reduction is reached at constant rpm only by changing the pitch,
2. ship speed reduction by reduction of rpm (and constant pitch),
3. ship speed reduction by a combination of rpm and pitch reduction (combinator curve).

Option1 leads mostly to an increase of the URN, while option 2 and 3 can lead to similar improvements than for FPPs with rpm reduction.

The effect can be used to lower the radiated noise of an existing ship fleet in selected areas, e.g. approach of port of Vancouver. Table 2 summarizes the reduction in speed and noise measured 2017 in the Vancouver Fraser Port Authority's Enhancing Cetacean Habitat and Observation program [18]. In [9] is given a numerical estimate lowering the ship's speeds to a hypothetical limit of 11 kn in the Kettegat (Sweden / Danemark) sea region leading to an average URN levels reduction of 4.4 dB. Note, that often the prognosis of URN reduction related to speed reduction do not consider the cavitation behaviour or only a general estimate of the cavitation inception speed.

Table 2. Noise reduction and speed reduction during slowdown test (measuring results from [18])

Vessel category	Mean speed red. [kn]	Mean noise red. [dB]	dB per kts of speed red.
Bulker	2.09	5.6	2.7
Containership	7.67	11.2	1.5
Cruise ship	6.15	10.7	1.8
Tanker	2.30	5.8	2.3
Vehicle carrier	5.89	9.2	1.6

Another noise reduction linked to speed reduction can be achieved with optimized logistics. A commercial ship travelling from one port to another tends to travel with an increased speed at the beginning of the journey and then slowing down, or even anchoring at a roadstead, when getting close to the arrival port. At this, the objective is not to miss the time slot in the arrival harbour. Nevertheless, considering EE, GHG and URN, travelling with a constant (design) speed would be preferable.

Running a ship for an extended period on reduced speed is likely to induce an adaption of the ship design speed. Hence, a new efficient propeller design will be a further consequence with potentially higher noise levels.

Speed/rpm reduction

Speed/rpm reduction is currently the best operational approach to considerably reduce the URN of a ship (especial if it features a cavitating propeller at normal operation speed).

Speed reduction - propeller efficiency

A ship propeller is designed to operate best at the design speed. Operating a propeller in off-design condition will lead mostly to less energy efficiency.

When running a ship for a longer period at another speed, a derating of the machinery and new propeller design with URN focus should be considered.

5.3 Cavitation control

For most ships and most operating conditions, a cavitating propeller dominates the URN. The knowledge of the cavitation inception speed (from model tests, sea trials, or online monitoring) is a criterion to what extent speed should be reduced.

5.4 Re-routing

Re-routing may improve underwater radiated noise in special protected areas by leading the ships around these areas. The overall effect however needs to be balanced with longer duration of emissions.

Yet another option could be to avoid shallow waters (the ship resistance increases in shallow waters) and profit of the smaller resistance while travelling through deeper waters.

The effect of re-routing ships in a special region is given in [23]. The main route for commercial ships in Kattegat (Sweden) was splitted into two: on route for large ships and on route for smaller ships closer to the coast. The splitting of the route caused an increase of the area which was affected by shipping noise.

5.5 Maintenance (Propeller and hull cleaning, AFS)

To operate the ship with best efficiency and best possible URN a good maintenance of the ship is necessary. In contrast to other measures, the benefit of maintenance addresses EE, GHG and URN as well. Note, that maintenance does not improve the URN of a ship but is only conserving the as-built status.

Remark:
Active anti-fouling systems working with ultrasound have the advantage of avoiding chemicals. However, as they operate at high frequencies, tend to disturb high frequency sensitive marine life [26].

6 Monitoring URN

6.1 Dedicated ship noise measurements

Measuring the URN of a ship during specific measuring campaigns e.g., during sea trials, is the most accurate approach to obtain the underwater radiated noise levels of a specific ship. However, these specific measurements are quite cost extensive and, in most cases, limited to a single ship draught, sea region and weather condition. An example of such measurements is documented in [9] (see also Figure 5).

There are multiple international standards, recommendations, and classification society rules how to perform measurements of ship noise. A corresponding (non-exhaustive) list is given in the IMO revised guidelines for the reduction of underwater radiated noise from shipping [33].

In [25] uncertainties are given, variation of 5 dB at low frequency bands and 3 dB for frequency bands higher than 100 Hz, for measurements of the same source gained at different ranges with similar sensor depths and comparable sea bottom properties at shallow water ranges. The information should make aware that corresponding measurements for qualification of mitigation approaches needs to be performed with greatest care according to the standards.

6.2 Measurements on sea (opportunistic)

Autonomous recording systems are deployed and constantly measure the prevailing noise level in the environment. Correlations with Automatic Identification Systems (AIS) of ships allow defining ship noise levels. While the AIS data include the distance to the measuring device, ship speed and some other ship specifics, no (reliable) data on e.g. propeller loading, draught or machinery are available. Thus, the evaluation lacks in depth.

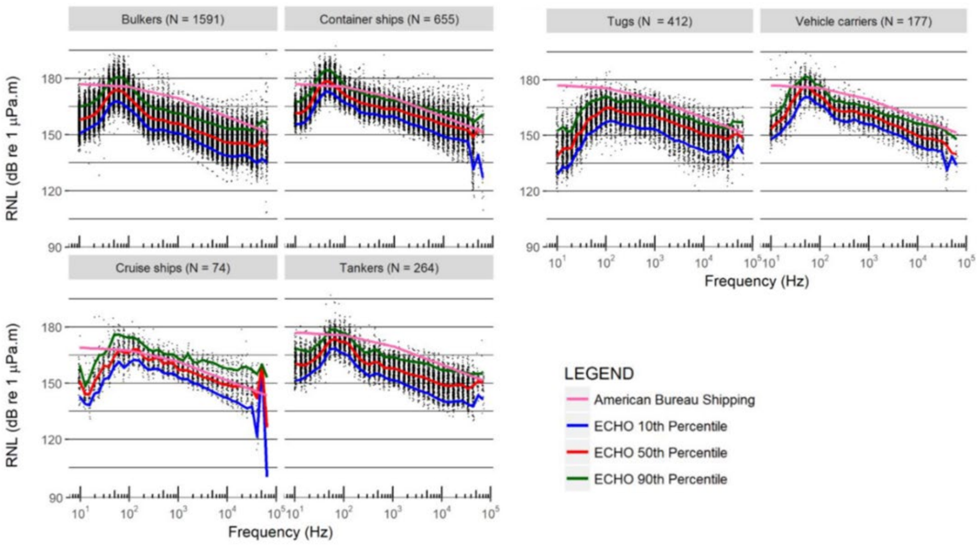

Figure 9 : Scatter plot of the scaled and adjusted RNL measurements according to the ABS class notation protocol overlaid with a frequency based percentile distribution (from [12])

This approach allows to measure large amounts of ships within a reasonable time span and thus to statistically evaluate the data. The most famous project of this kind is the ECHO station. The approach also allows quantifying if a ship is rather loud or not. Figure 9 (adapted from [12]) shows a comparison between the ECHO data and the the ABS class notation protocol. The ships within the ECHO 10th percentile and the ships within the ECHO 50th percentile (in most frequency ranges) are in line with class notation protocol.

Overall underwater noise

Opportunistic measurements show a large scatter in URN of different ship and ship types.

Regardless any classification (ship type, size, etc.) the real URN of a single should be evaluated preferably with dedicated URN measurements.

To effectively reduce the overall anthropogenic underwater noise the largest contributors should be addressed first.

6.3 Monitoring on board

Another approach to predict the URN is to use data monitored on board of a ship. Continuous monitoring allows to track the acoustical status of the ship and to compare it with operation related references. The predicted noise emitted into the water is available for further propagation calculations.

Uncertainties lie within the transfer path calibration between the on-board data and the underwater noise. Best practice is to perform individual calibration with underwater noise measurements.

(Ongoing) quality assurance

The URN of a ship shall continuously/regularly be monitored preferably with dedicated URN measurements.

Continuously: in the design stage, after initial operation, before and after conversion (retrofits), during normal operation.

Preferably with dedicated URN measurements: alternatives are opportunistic measurements or online monitoring, in design stage: predictions and model tests.

7 Abbreviations

ABS	Airborne sound
AFS	Antifouling system
CIS	Cavitation inception speed
CPP	Controllable pitch propeller
DP	Dynamic positioning
EE	Energy efficiency
ESD	Energy saving device
ESI	Environmental shipping index
FPP	Fixed pitch propeller
GHG	Greenhouse gas
IMO	International maritime organisation
NO_x	Nitric oxide (NO) and nitrogen dioxide (NO_2)
PM	Particulate matter (PM10 particulate smaller than 10 µm)
SBS	Structure-borne sound
Sox	Sulphur oxides (multiple type such as: sulphur monoxide SO, sulphur dioxide SO_2, sulphur trioxide SO_3, …)
TP	Transfer path
URN	Underwater radiated noise

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Appendix A

Questionnaire

Underwater noise from ships, noise abatement measures

Content of Appendix A:

1. Introduction
2. Questionaire
   a. Constructural/design measures
   b. Operational measures (cavitation control, speed reduction, etc.)
3. Acknowledgment

1. Introduction

There is already a considerable amount of very valuable work on reducing underwater noise caused by shipping operations.

Comprehensive questionnaires were examined e.g. in EMSA's SOUNDS project and the main results documented in the report "Status Of UNDerwater noise from Shipping" [11].

The objective of this questionnaire is, among other things, to obtain an expert opinion from research institutes, consultants, research project managers, etc., as well as classification societies and professionals from the field on the "qualitative and quantitative" potential of sound engineering and hydrodynamic planning. In addition, we would also like to identify constraints (e.g. energy efficiency) for the noise reduction target in this context. Not only the technical measures for the reduction of the sound input of individual ships, but also operational measures that lead to a reduction of the sound input by slow steaming, convoying, or rerouting, should be evaluated more closely.

2. Questionnaire

a. Constructural/design measures

Which optimized propulsion system is best suited for the respective ship types (container, bulker, tanker, passenger, ferry, offshore vessel, etc.) regarding energy efficiency and underwater noise?

- Most of the underwater noise is because of the cavitation at the propeller and hence generally independent of the type of propulsion system.
- The propulsion system currently are defined by the boundary conditions of each ship type. E.g. LNG Tanker often are equipped with twin shaft propeller system (for safety reasons), large container vessels are mostly equipped with single fixed propeller system (large distances at constant speed), ferries are commonly equipped with two shaft controllable pitch propellers (a lot of manoeuvring in harbours). Especially for commercial ships no extensive studies on which system is best for energy efficiency and urn have been done. State of the art is to optimize the commonly used system by hull, propeller, rudder optimization and use of energy efficiency devices.
  Most of the optimized systems often lead to less/better cavitation and therewith also to a better result in urn.
- No general answer possible, depends on the size of the ship and especially its operational profile.
-

Ship type	Reciprocating engine	Reciprocating engine + gen + e-motor	Gas turbine direct + PTI	Gasturbine + Gen +E-motor	FC or battery with E-motor
container	All sizes	-	Large ships		
bulker	All sizes	-	Large ships		
tanker	All sizes		Large ships	Large ships	

passenger		All sizes	Large ships		Smaller ships
ferry		All sizes			Smaller ships
offshore		All sizes			Smaller ships
tug					Smaller ships

- To date, most ships with URN requirements (fishery research, surface combatants) use the classical (fixed-pitch or controllable pitch) propeller system with tip-unloading combined with diesel-electric propulsion, but this is an expensive solution. There is ongoing research on improved solutions.
- Wake equalizing ducts.
- Propulsion systems design must fulfil the requirements from several stake holders. There is no rule of thumb for selecting the propulsion system for a certain ship type regarding URN.
- For large ocean going ships there is no alternative to two stroke engines and open screw propellers simply because they are unbeatable efficiency wise Global noise is a low frequency (< 300 Hz) issue and the one and only source is propeller cavitation, namely sheet cavitation.
  2-stroke engines and resiliently mounted 4-stroke engines are by far less problematic, if at all CIS is not well defined. There is a comprehensive study on this by Jasco. CIS can be understood as the speed where the gradient of noise with speed at blade rate increases. It is often linked to a model. In our model we use VCIS = 7 + 0.0164042 · L which comes from SNAME R&T Bulletin 3-37

For retrofit for ships, energy efficiency is currently a priority for the design of the propulsion system. What are the design challenges to consider besides energy efficiency also reduced URN?

- Presently prop modifications and ESDs are retrofitted for improving energy efficiency and to optimize operational profile. Underwater noise is at present not the main criterion. But usually, it is a trade-off…, more silent propeller tends to generally reduce propeller efficiency.
- As for new-designs, retrofits of commercial ship didn't have a focus on urn until lately. Our experience shows that a lot of focus is put on the topic, however the main focus lies on the energy efficiency. Often ships are built by one party, but not used (charter) by the same party, thus often these optimizations are not considered.
- No answer possible from our side, due to a lack of knowledge in the area.
- Guess that the acoustic improvement will be punished by a less efficient design. At the moment, shipowners look carefully at efficiency due to fuel costs and costs for CO_2 emissions.
- Not sure we understand the question, but the 'classical' design criteria are strength (especially for ice-going vessels but also for ships with electric motors), onboard noise and vibration, cavitation erosion, stopping/backing, influence of

wind assistance (unloading of propeller, oblique inflow), ventilation, off-design conditions such as manoeuvring & seakeeping.

- Data availability and Model generation.
- Difficult to name specific design challenges. Anyway, prediction of the URN in design phase and reliable comparison of design alternatives is one of the central challenges.

What is the acoustic improvement potential in optimizing ship lines and propellers per ship type and operating profiles? Please indicate the estimated source level reduction as well as the shift in cavitation inception speed. Can you provide references on this topic?

- Some studies have suggested that improvements to the propeller to reduce cavitation result in about 75% reduction in noise.
- HSVA sees most potential within the propeller design. We experienced large urn opportunities (~15-20dB) depending on the propeller design. Other features, energy efficiency devices, clean hull and propeller, will of course also have a positive effect on energy efficiency and urn, but in a lower order of magnitude. Reducing speed/loading is also reducing urn, however standard commercial ship propellers are likely to cavitate in all conditions and thus a certain urn level will never be fall below.
- No general answer possible, depends on the type of ship, the propulsion system and the acoustic measures, the ship already has. In addition, the achievable improvement is frequency dependent. An additional point is not only the cavitation inception speed (CIS) but also the type of cavitation. Some propellers, which have a rather high CIS might be noisier after the onset of cavitation at the same speed than others with lower CIS.
- This requires a more in-depth study as we don't have such data immediately at hand. We do now have all material available and recently developed the tools required to address this question in detail. These tools are currently applied for merchant vessels in research as well as commercial projects.
- No, should be studied.
- It is observed that two propellers for the same ship can be different by more than 10 dB.
  The control of sheet cavitation, namely the collapse of the large bubble has to be emphasized. The potential in noise reduction has been demonstrated to 10 up to 20 dB. Research into this aspect is only done at the University of Applied Sciences in Kiel.
  There is a quiet solution even without harming efficiency.
  The above is for low frequencies. Higher frequencies are even less understood, but it should be discussed how important this is compared to the low frequency issues.

Which innovative systems (e.g. air entrainment) are already marketable and promise significant level reduction? Were these results demonstrated in the laboratory and/or at full-scale?

- I have experience on Azipod vessels where a Bubbler system (which forces compressed air on the suction side of the propeller, significantly reduces noise and vibration.
- It is known that air lubrication systems have a positive effect onto the vibrations onboard. To what extend also urn is affected is not known to HSVA. Model tests

regarding this issue are difficult, since bubble scaling are hardly possible.
Bow thrusters equipped with anr may reduce urn.

- Prairie system (Propeller air emission system) improves the URN level for high-speed sailing, where propeller cavitation is fully developed. However, might increase low frequency noise, especially at non cavitating conditions.
- We have successfully demonstrated in a laboratory the potential of using air-injection below the hull to reduce the noise by hull vibrations (excited by e.g. machinery equipment) and air injection into the propeller disc to reduce the noise by cavitation. Preliminary results have been published in the SATURN newsletter of February 2023, and more detailed results will be presented at the IMO URN-EE workshop.
- Wake equalizing ducts but currently no design approaches regarding noise reduction.
- Marketing: OSCAR (PressurePoresTM) promises 10 dB reduction. https://maritime-executive.com/corporate/oscar-propulsion-reduces-underwater-noise Associated journal paper: Suppression of Tip Vortex Cavitation Noise of Propellers using PressurePoresTM Technology. Journal of Marine Science and Engineering, Vol 8, Iss 3, p 158 (2020). https://doi.org/10.3390/jmse8030158
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- No comment.

Coatings for propellers can promote propeller singing in the non-cavitating case. Can this be avoided in the design?

- It is usually possible to design propellers with noise reduction.
- If a propeller is singing small modifications of the propeller trailing edge with an angle grinder are a fast solution to this issue.
- Coatings might amplify propeller singing, especially, if the propeller tends to sing, anyway, without the coating. It is important to verify, that an anti-singing trailing edge is still functioning after coating. Taking care of the thickness of the coating in order to retain the hydrodynamic properties of the propeller is essential.
- The flow field for the propeller is very complex and the effort is very high to perform time resolved calculations, which might reveal the occurrence of vortex shedding as the main reason for propeller singing. From economical point of view, the risk for singing is taken and countermeasures are introduced later, if there is such a rare case.
- Yes, by applying an anti-singing edge on which the coating should not be applied.
- With anti-singing trailing edge designs.

- Using simulation tools and proper designs, why not. Need to be able to simulate hydro-vibro-acoustic behaviour of the propeller and blades. Experiments too, of course. Coatings with high structural damping might have potential.
- Singing can always be avoided by anti-singing edges. I have never seen a case where this was not successful.

Which alternative propulsion systems promise significant potential for improvement for which ship type? Please indicate the estimated source level reduction relative to conventional propulsion systems, e.g. cycloidal propeller.

- Not aware of estimations.
- VSP, podded drives show often low noise levels, since the propeller is operating in a clean wake field. These drives are nowadays in cruise ship, etc.
- No general answer possible from my side. We don't have enough experimental experience with alternative propulsion systems.
- There are several systems being investigated (preswirl stators, wake-equalizing devices, gated rudder, pumpjets, cycloidal propellers) but we have not yet analysed them ourselves for their URN properties.
- Alternative propulsion systems mimic the movement of tails and fins of marine animals. Naming depends on operation of the system e.g. trochoidal, cycloidal, flapping foil etc.?? Research needed.
- No comment.

Ships that operate stationary need positioning units. What low-noise propulsion systems are available? Are there any performance studies (with respect to URN) available?

- Not aware of performance studies.
- Thruster systems with active noise reduction systems, cycloidal propeller or podded drives are likely to reduce urn in stationary positioning units.
- No dedicated studies on stationary systems available to my knowledge. VSP are probably less noisy than thrusters or pump jets. Same holds for rudder propellers, as long as cavitation can be avoided.
- Not available to us.
- The cavitation noise of azimuthing thrusters at (near) bollard pull, typical for DP-ing ships, has been investigated by model tests in the NAVAIS EU-project. Information about the noise from bow thrusters is also available. However no design studies to minimize the noise during DP have been performed at MARIN so far.
- Tunnel thruster with air bubble curtains/noise suppression.
- There is some information concerning water jets. For example: "The radiated noise was 10–20 dB lower than noise from propeller-driven ships at comparable speeds. The combination of low radiated noise and high speed could be a factor in the detection and avoidance of water-jet-propelled ships by baleen whales." Book (Springer, 2016): Arthur N. Popper • Anthony Hawkins, Editors. The Effects of Noise on Aquatic Life II, Chapter 117 Radiated Sound of a High-Speed Water-Jet- Propelled Transportation Vessel.
  Also this should be studied more.
- DP: quietest thrusters are rim-drives and fixed pitch, speed controlled with air injection

Due to the excitation frequency spectrum and the weight of propulsion systems with 2-stroke drives, elastic decoupling is not effective acoustically according to the current state of the art, which leads to the limitation of sound reduction of optimized propellers. Are there any more recent findings?

- Not aware of recent findings.
- I don't think, that this statement is correct in its generality. Diesel engines are the dominant noise source at the low frequency end of the spectrum. Cavitating propellers are responsible for broad band noise up to very high frequencies. Thus, different noise reduction measures have to be considered over the whole frequency band. However, I'm not aware of any recent findings, regarding elastic mounting of large two stroke Diesel engines.
- We are dealing with electric propulsion only.
- Air injection below the hull might be an interesting solution to mitigate the sound of 2-stroke engines.
- The physics behind this is that there is no gearbox, just direct drive in large 2-stroke engines. The excitation frequencies are low in low-speed engines and the isolated masses are large (difficult to isolate). 2-stroke engines are simple. They have higher power to weight ratio compared to 4-strokes and thus they have big advantages to use in large ships.
  Literature checks needed here as well.
- No comment.

b. Operational measures (cavitation control, speed reduction, etc.)

Rerouting of ship routes is seen as a measure for the protection of protected areas. Based on the studies carried out, are there any practical recommendations that should be considered in planning new shipping routes?

- Re-routing is highly dependent on the type of vessel and operational profile. On passenger ships, it may not be practically possible to re-route unless itineraries are changed.
- In most case a ship is optimized for one (maximum two) draught and one (maximum two) speed, which is defined in the contract with the yard. In order to get bests results in daily operation, ship routes and travelling profiles should be considered already in the design stage. As already mentioned often the party building a ship is not operating a ship and thus has only very few interests (and of course also knowledge) in these optimization. Shipping companies which are building there own ship already nowadays consider the routing in the design.
- Rerouting has to consider the possible ship speeds as well as additional time and fuel consumption. Slow steaming might be an alternative, if the ship has a suitable propulsion system.
- Availability of renewable energy carrier (methanol or H2 or others) becomes an important matter. The applicability of FC or batteries as energy converters depends not only on the size of consumers but also on the distance between "refueling" stations. Due to the current state of the art (and in the near future) their capacity is a considerable constraint. Larger distances could kill such projects.
- ?
- No comment.

Slow steaming has the best effect from an acoustic point of view when the propeller no longer cavitates or cavitates only weakly. How should the cavitation inception speed be checked? Are there rules for individual ship types and propulsion systems?

- As propellers are individually designed, it may be prudent to measure the noise levels in operation to check actual noise levels.
- It is very likely that standard commercial ships propeller will show cavitation (at least tip vortex cavitation) at all velocities. Recent research shows however that non-bursting tip vortex cavitation has a much lower urn than other cavitation types, thus slow steaming should always be considered when need of urn reduction (e.g. in certain special habitats) is required.
  Cavitation inception can be measured in design stage during cavitation tests in model basins (https://www.ittc.info/media/8035/75-02-03-031.pdf). Cavitation inception can be predicted in the propeller design. Cavitation inception can also be detected during sea trial.
- Statement is not correct in its generality. If slow steaming reduces cavitation, depends on the propulsion system. Especially for propulsion systems with CPP, slow steaming might be noisier than the usual operational speed. Cavitation inception speed (CIS) can be determined experimentally by increasing the speed step by step and observing the cavitation behaviour. CIS should be checked acoustically, since increased noise spectra are already noticeable before cavitation bubbles are observable optically.
  Different criteria can be checked at certain speeds to prove, if propeller cavitation occurs:
  1. Listening to the sound for characteristic cavitation noise
  2. Increased levels in the acoustic broad band spectrum starting at the high frequency end of the spectrum
  3. DEMON analysis of acoustic signals to prove the modulation of the signal with the propeller rpm.

  At least two of the three criteria should be fulfilled to prove cavitation inception. We recommend to use stand off hydrophones for the measurement. Onboard sensors might be not feasible, if other dominating structure borne sound sources are in the vicinity of the sensors (masking of the relevant cavitation signature).
- Cavitation inception is one of the key issues in the design of naval ship propellers. There are requirements in respective rules (e.g. Class Societies) available. The aim is to obtain a high cavitation inception speed.
- Onboard monitoring systems using accelerometers and pressure sensors mounted on the hull above the propeller can be used for that purpose. The cavitation inception speed can be checked by using a threshold on the levels or by using DEMON.
- Pressure or vibration sensor system for cavitation identification
- Slow steaming is quiet only if a ship is designed for high speed but sails slow. If the ship is designed for the same low speed it is about as noisy as the fast ship because the extent of cavitation allowed is roughly the same for all propellers to maximize efficiency

Maintenance, e.g. propeller and hull cleaning are essential to maintain the acoustic properties of a vessel. Do you have practical experience about the necessary cycle?

- Propellers and hull are cleaned during its dry dock cycle (twice every 5 years).

- At first a clean hull and propeller is affecting the energy efficiency of the ship. With a poorly maintained ship higher energy consumption and propeller loadings are likely and thus results in higher urn. Nevertheless, the gain (bringing back to best conditions) is not comparable to the gain in an optimized propeller design.
- There are several assisting tools on the market available that enable an optimized cycle for cleaning. However, their aim is an optimization regarding efficiency (consuming more fuel) and costs for cleaning. The influence on the acoustic behaviour is not considered so far, but could be introduced there as a boundary condition, which could lead to an earlier cleaning.
- No.
- No.
- No comment.

Do you know of any studies on the sound emission of AFS systems that are ultra-sound based?

- https://www.nature.com/articles/s42003-022-03959-9
- I'm neither aware of any study as regarding the URN of those systems, nor do I have knowledge about the frequencies at which those systems operate.
- No.
- See https://marine.gov.scot/sites/default/files/underwater_noise_technical_assessment_a-100142-s20-tech-001-a01_0.pdf: "Driven by a 23 kHz sinusoidal ultrasound in an intermittent manner, the projectors emitted a high-intensity sound reaching 214 dB at the source level causing cavitation around the adjacent water and eventually deterring the settlement of marine fouling organisms."
- AFS = Anti-Fouling System?, https://www.marineinsight.com/tech/4-types-of-anti-fouling-systems-used-on-board-ships-to-prevent-marine-growth/
- Cleaning based on cavitation works like the common ultrasonic cleaning?
- No comment.

3. Acknowledgment

Answer to the questionnaire came from:

- Consultants for ship, offshore and underwater acoustics,
- Experts from research institutes (e.g. model basin, technical departments, propeller design),
- Industry experts (e.g. manufacturer of engines), and
- Representatives from public authorities.

Many thanks for the extensive replies to the questionnaire.