TP 15411 E

Vard Marine Inc.

SHIP UNDERWATER RADIATED NOISE

Report 368-000-01

Rev 4

Prepared for

Innovation Centre

Of

Transport Canada

by

Vard Marine Inc.

Date: 12 February 2019

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Andrew Kendrick and Rienk Terweij
Vard Marine Inc.

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NOTICES

This report reflects the views of the authors and not necessarily those of the Innovation Centre of Transport Canada.

The Innovation Centre does not endorse products or manufacturers. Trade or manufacturers' names appear in this report only because they are essential to its objectives.

The report is available in English only.

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Un sommaire français se trouve avant la table des matières.

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17. Abstract

This report presents the results of a review of means of mitigating and predicting the underwater radiated noise (URN) from ships. This noise can have significant environmental impacts, with damaging effects on marine animals of many types.

The main outcome of the work undertaken is a matrix of URN mitigation measures. Measures are categorized in four main areas, covering propeller noise reduction; machinery noise reduction; flow noise reduction; and other, where the first three categories are not easily applied.

Each measure is described, and then defined in a standardized approach that aims to define the advantages and benefits to the ship's design and operations; disadvantages and challenges; technology readiness; cost impacts for implementation and operation; applicability to different ship types; and effectiveness; in terms of frequency ranges and reduction in sound levels. A final section of the matrix provides a summary of prediction methods for URN.

A wide range of mitigation measures are available to address different types of noise at varying levels of effectiveness. All will incur some level of cost, but in some cases there are co-benefits such as efficiency enhancements that may offset some or all of this disadvantage.

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17. Résumé

Ce rapport présente les résultats d'un examen des méthodes d'atténuation et de prévision du bruit rayonné sous l'eau émis par les navires. Ce bruit peut avoir des incidences environnementales importantes et des effets dommageables sur de nombreux types d'animaux marins.

Le principal résultat des travaux entrepris est une matrice des mesures d'atténuation du bruit rayonné sous l'eau. Les mesures s'inscrivent dans quatre grandes catégories, notamment la réduction du bruit des hélices, la réduction du bruit des machines, la réduction du bruit d'écoulement, et les autres mesures, lorsque les trois premières catégories ne s'appliquent pas.

Chaque mesure est décrite, puis définie selon une approche normalisée visant à définir les avantages et bénéfices pour la conception et l'exploitation des navires, les inconvénients et les défis, l'état de la préparation technologique, les répercussions liées aux coûts de mise en œuvre et d'exploitation, l'applicabilité à différents types de navires et l'efficacité en ce qui a trait aux gammes de fréquences et à la réduction du niveau sonore. La dernière section de la matrice résume des méthodes de prévision du bruit rayonné sous l'eau.

Une vaste gamme de mesures d'atténuation est disponible pour aborder les différents types de bruit selon divers niveaux d'efficacité. Elles sont toutes associées à des coûts mais, dans certains cas, les avantages connexes, comme une amélioration de l'efficacité, peuvent compenser ces inconvénients, en tout ou en partie.

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3	9 Jan 19	Incorporation of TC comments	AK	MB
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EXECUTIVE SUMMARY

This report presents the results of a review of means of mitigating and predicting the underwater radiated noise (URN) from ships. This noise can have significant environmental impacts, with damaging effects on marine animals of many types. The report provides an overview of URN issues but is not intended as a complete guide to this very complex subject.

The main outcome of the work undertaken is a matrix of URN mitigation measures, presented as Appendix A to the report, which can be used as a stand-alone summary of options that can be used now and in the future. Measures are categorized in four main areas:

1. Propeller noise reduction;
2. Machinery noise reduction;
3. Flow noise reduction; and
4. Other, where the first three categories are not easily applied.

Each measure is described, and then defined in a standardized approach that aims to define:

- Advantages and benefits to the ship's design and operations;
- Disadvantages and challenges;
- Technology readiness;
- Cost impacts for implementation and operation;
- Applicability to different ship types;
- Effectiveness; in terms of frequency ranges and reduction in sound levels.

A final section of the matrix provides a summary of prediction methods for URN.

Entries in the matrix are supported by citations, and a full list of references is provided in Appendix B to the report.

A wide range of mitigation measures are available to address different types of noise at varying levels of effectiveness. All will incur some level of cost, but in some cases there are co-benefits such as efficiency enhancements that may offset some or all of this disadvantage.

RESUMÉ

Ce rapport présente les résultats d'un examen des moyens d'atténuer et de prédire les bruits rayonnés sous l'eau émis par les navires. Ces bruits peuvent avoir d'importantes répercussions environnementales, avec des effets néfastes pour de nombreux types d'animaux marins. Le rapport fournit un aperçu des enjeux des bruits rayonnés sous l'eau, mais n'a pas pour but d'être le guide complet de ce sujet très complexe.

Le principal résultat des travaux entrepris est une matrice de mesures d'atténuation des bruits rayonnés sous l'eau, présentée à l'annexe A du rapport, qui peut être utilisée comme un sommaire des options pouvant être utilisées maintenant et à l'avenir. Les mesures sont classées en quatre principaux secteurs :

1. Réduction du bruit d'hélices;
2. Réduction du bruit des machines;
3. Réduction du bruit d'écoulement;
4. Autre, lorsque les trois premières catégories ne s'appliquent pas facilement.

Chaque mesure est décrite et ensuite définie selon une approche normalisée visant à définir :

- Les avantages et bénéfices pour la conception et l'exploitation du navire;
- Les désavantages et les défis;
- L'état de la préparation technologique;
- Les répercussions des coûts pour la mise en œuvre et l'exploitation;
- L'applicabilité à différents types de navires;
- L'efficacité, en termes de gammes de fréquences et de réduction des niveaux sonores.

Une section finale de la matrice fait le résumé des méthodes de prévision pour les bruits rayonnés sous l'eau.

Les entrées dans la matrice sont appuyées par des citations et une liste complète des références est fournie à l'annexe B du rapport.

Une vaste gamme de mesures d'atténuation est disponible pour traiter différents types de bruits à différents niveaux d'efficacité. Elles nécessitent toutes certains coûts, mais dans certains cas il y a des avantages connexes, comme les améliorations d'efficacité, qui pourraient compenser ces désavantages en tout ou en partie.

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1 INTRODUCTION

This report presents the results of a review of means of mitigating and predicting the underwater noise radiated by ships. This noise can have significant environmental impacts, with damaging effects on marine animals of many types.

Vard Marine (VARD) has been engaged for this work by the Innovation Centre of Transport Canada (TC). TC is a lead department for Canada's domestic Oceans Protection Plan, and also for work with the International Maritime Organization on international measures aimed at protecting the marine environment. TC needs to acquire information on the technological measures that have been currently implemented or that could be implemented (bleeding edge technologies) to reduce Underwater Radiated Noise (URN), in order to reduce impacts on marine mammal life.

VARD's analysis of the technologies applicable to different vessel classes includes its capacity to reduce underwater vessel noise, cost, ancillary benefits (i.e. reduced fuel consumption and emissions), expected payback period (if applicable) and any other considerations or barriers to implementation. This information will help TC prioritize further research and analysis related to underwater noise reductions for the domestic fleet. The report is also intended to inform other initiatives planned by the Department and to support broader information dissemination.

Our report provides the content for the work, and the methodologies that have been used to assess a wide range of technology options. Its scope does not address operational methods of noise reduction in depth (slow steaming, etc.), as these are the subject of parallel research programs. The main outcome of the work is a Matrix of options and aspects, presented as an Appendix to the report, which can be used as a stand-alone summary of URN reduction measures that can be used now and in the future.

This report does not attempt to provide a comprehensive description of any aspect of URN, which is a vast and complex subject. This is an introductory treatment, supported by reference to more in-depth explorations of one or more aspects of the field. The report also does not aim to endorse or recommend any specific approach to URN mitigation. Where opinions and assumptions are included, they are those of Vard Marine's project team, and should not be taken to represent any position or policy on the part of Transport Canada.

2 NOISE SOURCES – OVERVIEW

“Noise” is a term used for unwanted or unpleasant sound. Physically, acoustic sound is a phenomenon created by the transmission of waves by an emitter, and through a medium to a receiver such as the human ear or another suitable sensor. Sound can be created in many ways; by natural phenomena such as wind and wave actions, ice interactions, landslides and earthquakes; by animals using a multitude of techniques, and by humans (anthropogenic) either deliberately for music, exploratory investigations (seismic, echo-location, etc.), or as a by-product (machinery and process noise). Anthropogenic sound, or noise, causes distress and irritation to humans, generally when transmitted through the air.

Sound waves in the frequency ranges usually considered acoustic travel with less attenuation (for longer distances) through water than through air. Anthropogenic sound waves in water are used extensively for exploratory purposes and generated even more extensively as by-products through the operation of ships and other offshore systems. Seismic exploration, military sonars, commercial echo-sounders and fish-finders are all significant sound and noise sources of concern in some areas but fall outside the scope of this project. The focus here is on noise generated by ships in their transiting operations, which can be categorized as:

a. flow noise,
b. machinery noise, and
c. propeller (propulsor) noise.

2.1 SHIP NOISE SOURCES

The passage of a ship through the water creates pressure fields that in turn are the sources of waves of various types, including the visible ship wake spreading out from the hull and sound waves. In calm water and at low speeds this flow noise is of low intensity. It increases as speeds increase, and when ship motions increase in wind-generated waves. However, flow noise is generally not considered a significant problem. Another form of “passage” noise, is icebreaking. Icebreaking is an energy-intensive process that creates considerable audible noise both airborne and waterborne. Icebreaking noise is still generally at lower levels of intensity than the machinery and propulsor noise required to accomplish icebreaking.

Machinery noise arises from all rotating and reciprocating equipment operating on board a ship. In general, the more imbalance there is in a machine, the higher the intensity of the noise and vibrations it will generate for any power level. Rotating machines, such as turbines, are easier to balance than reciprocating machines, such as diesel engines. Gear noise is generated when gear teeth engage as shafts rotate. There are other sources, such as flow noise in pipes and air ducts which can also be an issue, but more for the crew than as underwater noise sources.

Noise can be reduced at source, by making the machines run more quietly. Improving balance, tightening tolerances, changing geartooth profiles and many other means are used for this.

Marine machinery benefits from advances in other vehicle and power generation technology, where noise levels are being driven down by societal and competitive pressures.

There are many transmission paths from any machine emitting noise into the water, but they are often characterized as airborne and structureborne. The noise a human hears next to a machine is transmitted to the air to the hull, exciting vibrations of the hull structure that generate sound vibrations in the backing water. In structureborne noise, the vibrations transmitted by a machine into its foundations and connected systems then also excite the hull structure and generate underwater noise. All these noise paths can be treated. Machines can be surrounded by an acoustic enclosure. Resilient mounts can impede the transmission of vibration. Damping treatments can be applied to the structure to absorb energy. All of these options are discussed in later sections of this report.

Propeller, or propulsor noise is not completely unique to the marine industry but different phenomena in air and water make the problem different from that in the aviation industry (or wind energy). The passage of a propeller blade through the water creates flow noise, which is aggravated by the uneven wake field behind the ship. As each blade moves through a fluctuating pressure field, this sets up pulses of sound energy; this is similar to propellers and turbines in air. However, for ship propellers the phenomenon of cavitation creates higher intensity noise. Low pressure is created over the propeller airfoil section, at blade tips, and at the hub. This can become low enough that the water essentially “boils”. Cavitation bubbles form, move into areas of higher pressure, and then collapse. The collapse can be very rapid and creates high pressure pulses that are intense enough to damage the propeller blades or the rudder often found behind them. This also generates a great deal of noise. For most ships with variable speed propellers, there is a cavitation inception speed above which this becomes the predominant noise source.

2.2 NOISE CHARACTERISTICS

Different noise sources have different frequency characteristics. Much machinery noise has most of its energy at discrete frequencies, such as engine firing rate and its harmonics (multiples). If a diesel engine is run at varying speed, these frequencies will change accordingly. For a generator set designed to create 60 Hz (cycles per second) current, engine speeds will be aligned to this, using values such as 720, 900 or 1200 rpm (revolutions per minute) and appropriate gearing. Similarly, much equipment driven from the ship service electrical power will also generate frequencies related to the 60 Hz value. Flow and propeller noise, including cavitation, is more broadband; i.e. the energy is distributed across a wide range of frequencies. Noise treatment methods may be more, less or equally effective against narrow- and broadband sources.

The loudness of any sound is usually referred to in terms of decibels (dB). dB are expressed in logarithmic terms, related to some reference values. This means that if two adjacent noise sources each produce 100 dB, when both are operating the total noise is 103 dB, not 200. Similarly, reducing the noise energy in half will only reduce the dB value by 3. Sound power or pressure levels in air are by convention linked to different reference values to those in water, therefore 100 dB in airborne noise does not mean the same as 100 dB in water. This should be appreciated when, for example, trying to relate the airborne noise in a ship's engine room to the noise levels in the water outside the hull.

3 NOISE EFFECTS ON MARINE LIFE

Both the loudness and the frequency at which sounds are produced will determine the level of impact on marine species and terrestrial species. Figure 1 shows how the frequency of shipping related noise overlaps with the hearing frequency of many marine species.

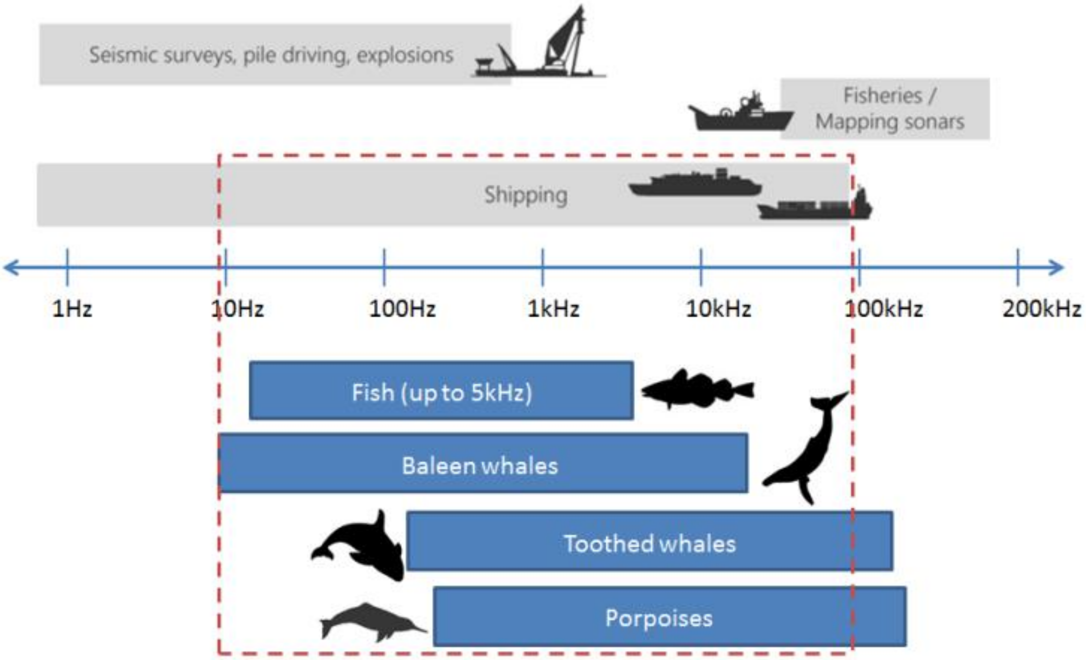

Figure 1: Overlap of Selected Emission and Hearing Frequencies[1]

Many scientific studies have explored the effects of anthropogenic noise on marine life ranging from invertebrates to fish and marine mammals. These include:

- Physical damage, from loss of hearing to death;
- Masking communications, affecting mating and other interactions;
- Reduced foraging activity, particularly where animals use sound to locate prey;
- Increased stress levels, with overall adverse impacts on health, in a wide variety of species;

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[1] Figure from MEPC 73/INF 23.

- Behavioural modification, including avoidance of high noise areas that may also be preferred habitats.

These adverse impacts are particularly acute for populations that are already under threat from habitat loss, over-harvesting, and other stressors, such as some of the whale species around Canada's coasts.

It is generally accepted that the world's seas and oceans are becoming noisier. Figure 2 shows one example of recent studies, showing a doubling (3dB) of noise intensity every decade at one sampling location. Other areas show similar trends. While species have widely varying levels of noise tolerance, without action more and more will become affected by increasing URN.

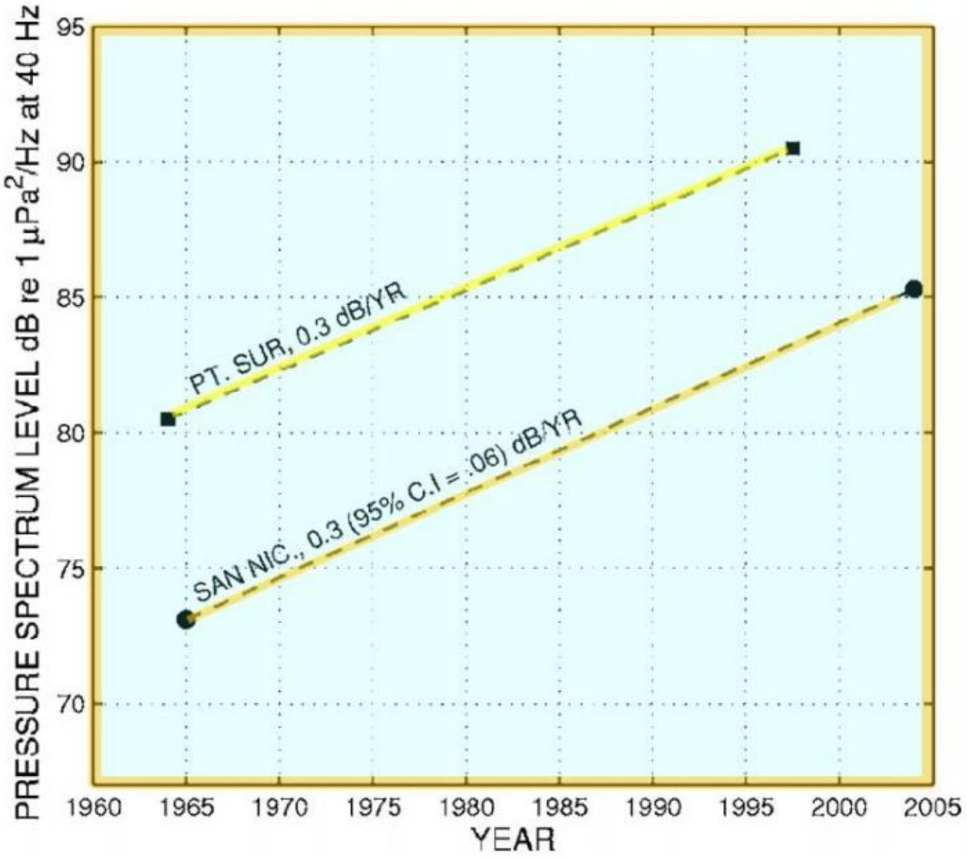

Figure 2: Increases in Ambient Noise with Time, NE Pacific[2]

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[2] McDonald, Mark A., John A. Hildebrand, and Sean M. Wiggins. "Increases in deep ocean ambient noise in the Northeast Pacific west of San Nicolas Island, California." The Journal of the Acoustical Society of America 120.2 (2006): 711-718.

4 URN MATRIX

4.1 OVERVIEW (ORIGIN OF MATRIX, ASPECTS ADDRESSED, INFORMATION SOURCES)

A matrix was used to summarize various URN mitigation and prediction methods at one of the earlier international discussions of this issue, hosted by the US National Oceanic and Atmospheric Administration (NOAA) in 2007[3]. This earlier matrix was the starting point for the development of the version for this project and has been updated and extended to provide a more comprehensive and up-to-date overview of potential options.

The matrix itself is included at Annex A to this report. It includes a summary of each option, and in most cases references to information sources used in compiling the matrix. The following sub-sections of the report provide additional explanation of how the information has been organized and how it should be interpreted.

In some areas, the assessments made are those of Vard Marine, and are based on our engineering judgement and assessment. This has been done in good faith, and without any commercial interests being involved. However, we recognize that differences of opinion may arise in such cases unless and until actual physical data is gathered to validate and quantify performance claims.

4.2 GENERAL CATEGORIES (PROPELLER, MACHINERY, FLOW NOISE, OTHER)

The noise control options have been consolidated into a set of general categories including flow noise, machinery noise and propeller/propulsor noise as described in Section 2.

In some cases, a technology may be an enabler of noise reduction without necessarily leading directly to it. As an example, using electric transmission rather than direct drive from a prime mover (engine) through a shaft to a propeller does not necessarily reduce noise. It does however simplify noise reduction through various measures, including more efficient isolation mounts, removal of gear noise, relocation of noise sources away from the hull, etc.

A final set of noise control options are categorized as “other”, where they do not fit neatly into the three main categories. This includes various forms of wind-assisted propulsion which can wholly or partially remove the need for conventional machinery.

Noise prediction methodologies are included as a separate set of matrix entries.

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[3] Final Report of the National Oceanic and Atmospheric Administration (NOAA) International Symposium “Potential Application of Vessel-Quieting Technology on Large Commercial Vessels” May, 2007 Silver Spring, Maryland, U.S.A.

4.3 DESCRIPTION

The first column in the matrix provides a summary of the mechanisms by which a mitigation measure operates. For example, does it reduce noise at source or by treating the transmission path; if propeller noise is reduced then how and why. This column also indicates one or more reference documents that provide more detail on the method and/or provide examples of its use in the marine field.

4.4 POTENTIAL ADVANTAGES AND BENEFITS

The advantages and benefits column indicates whether a measure has benefits beyond noise reduction, such as an increase in efficiency or a reduction in some other forms of emission (see also Section 5). Obviously, many noise reduction measures will benefit not only the underwater signature but also the comfort of crew and other persons on board such as passengers, scientists or offshore workers.

In this column of the matrix, a set of codes are used to identify common types of advantage and benefit. In some cases additional notes are provided to clarify aspects of the potential use. The codes include:

CC - Enhanced Crew/passenger Comfort
E - Reduced Emissions
F - Enhanced eFficiency
M - Reduced Maintenance
MA - Increased MAneuverability
S - Decreased Space Demand
W - Decrease in Weight

In a few cases, other potential advantages are described where these are unique to a single measure; for example, hull polishing removes biofouling which is a transmission vector for invasive species.

4.5 POTENTIAL DISADVANTAGES AND CHALLENGES

Almost all noise reduction measures will have some form of disadvantage, often related to the cost of implementation and also in many cases to a reduction in the functionality of the ship, by occupying space, consuming additional power, adding maintenance effort, and other factors. As with advantages, the matrix uses a set of codes to classify significant disadvantages of these and other types. Proponents are less likely to highlight disadvantages than advantages, and so many of the assessments in this area are based on VARD's ship design experience.

The codes used in this column are in most cases the opposite of the advantages, and include:

D - Increased Design effort
E - Increased Emissions
F - Reduced eFficiency
M - Increased Maintenance
MA - Reduction in MAneuverability
P - Increased comPlexity
S - Increased Space demand
W - Increased Weight

For both disadvantages and advantages an attempt has been made to consider the impact on the ship as a whole, though this is often dependent on other factors such as the operational profile of the ship. For example, electric propulsion is inherently less efficient than mechanical, due to losses in power generation and conversion. However, it can be used to optimize engine loading, to introduce stored energy systems, and to allow for other efficiency enhancing measures. In these cases it can provide net improvements in efficiency.

4.6 TECHNOLOGY READINESS

VARD has used the Technology Readiness Level (TRL) method to classify the maturity of each mitigation measure. TRL was developed by NASA and is increasingly used by organizations including Transport Canada to indicate the status of a wide range of technologies. The definitions used by Innovation, Science and Economic Development Canada (ISED) are shown below; most others are very similar. TRL 1 represents “blue sky” concepts while TRL 9 is mature and in widespread service.

> **TRL 1: Basic principles observed and reported:** Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology's basic properties.
>
> **TRL 2: Technology concept and/or application formulated:** Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions.
>
> **TRL 3: Analytical and experimental critical function and/or characteristic proof of concept:** Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology.
>
> **TRL 4: Product and/or process validation in laboratory environment:** Basic technological products and/or processes are tested to establish that they will work.
>
> **TRL 5: Product and/or process validation in relevant environment:** Reliability of product and/or process innovation increases significantly. The basic products and/or processes are integrated so they can be tested in a simulated environment.

TRL 6: Product and/or process prototype demonstration in a relevant environment: Prototypes are tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a simulated operational environment.

TRL 7: Product and/or process prototype demonstration in an operational environment: Prototype near or at planned operational system and requires demonstration of an actual prototype in an operational environment (e.g. in a vehicle).

TRL 8: Actual product and/or process completed and qualified through test and demonstration: Innovation has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development.

TRL 9: Actual product and/or process proven successful: Actual application of the product and/or process innovation in its final form or function

VARD has assigned TRL to each method in the matrix, based on our own understanding. As many measures at lower TRLs are kept quite confidential until ready for market, it is possible that some are more mature than indicated. Obviously, any promising concepts that have not yet been publicly revealed cannot be included in the matrix. The matrix is a snapshot in time that should be updated in the future.

While a number of measures have been classed as TRL 9, at this level there can still be substantial differences in the level of application by the industry, and between ship types. Electric transmission systems, for example are widely used in smaller vessels and in a few larger types, such as cruise ships; but not in tankers, bulkers or container ships. This is mainly due to different economic drivers. Often a new technology will see its first applications in specialized vessels and then move gradually into other areas of commercial shipping.

4.7 COST IMPACT

A number of different metrics for the cost impact of noise reduction measures are used; relating these to the cost of the item (e.g. propellers), absolute cost, and other metrics. For some measures that also offer efficiency gains the proponents often claim payback periods; i.e. the time required for recovery of the investment in fuel cost savings. Where payback period have been claimed, these values are cited. If no such estimates have been found this is left blank.

All of these numbers should be considered very approximate. The differences between ships and ship types mean that the absolute values of cost will vary widely, as will the percentage of a ship's value that any measure represents.

4.8 APPLICABILITY

Some measures may be applicable only to the building of new ships, while others may also be possible for retrofits or modernizations. A conversion to diesel-electric propulsion, or a change from shafted to podded propulsors may not be technically feasible for most existing ships, for example. The changes required to internal configuration, hull form or other overall ship parameters may be impractical.

The codes used in this column are:

New Build	-	NB
ReFit	-	RF

For many refit items the ship must be taken out of the water to implement the measure. This applies to all propeller and flow noise treatments, and many for machinery. The cost of dockings has not been considered as part of the cost impact, as it is assumed that the measures would be implemented alongside other scheduled work.

The second aspect of applicability considers the types of ships which could utilize the technology or methodology. Ships that operate for all or significant parts of their voyage profile at low speeds are most likely to benefit from machinery noise reduction. Those that operate mainly at higher speeds will benefit more from propeller noise reduction; e.g. by increasing the cavitation inception speed. Many ships have higher and lower speed operations over some part of their voyage profiles, so that both machinery and propeller noise reductions may be valuable.

A wide variety of ship types and sizes sail the world's oceans and coastal waters. Figure 3 shows some examples, categorized by size and speed as being two of the key parameters. Many types do come in a wide range of shapes and sizes; for example ferries, which can be large, small, slow or fast. The quadrants of the figure have been numbered for ease of referencing in the matrix.

In general most techniques will be broadly applicable. Exceptions come where ship characteristics make a technique infeasible. For example, large and high powered ships often use extremely large and heavy low speed diesels, which are very difficult to raft mount (see Appendix A, item 2.2.3). Ship types on short routes and fixed schedules are unlikely to use wind-assist technologies. In the matrix, quadrants 1, 2, 3 and 4 of Figure 3 are used to identify which methods are most applicable to which ship types. Where this is challenging for certain types a note is added to explain why.

Other exceptions may exist due to specific design drivers. Ice class ships for example have to have strengthened propeller blades and high power. This can limit the use of noise reduction technologies focused on blade shape and loading distribution. Shallow draft vessels will have restrictions on propeller diameter, leading to high loadings. In general, all ship designs balance conflicting drivers and constraints.

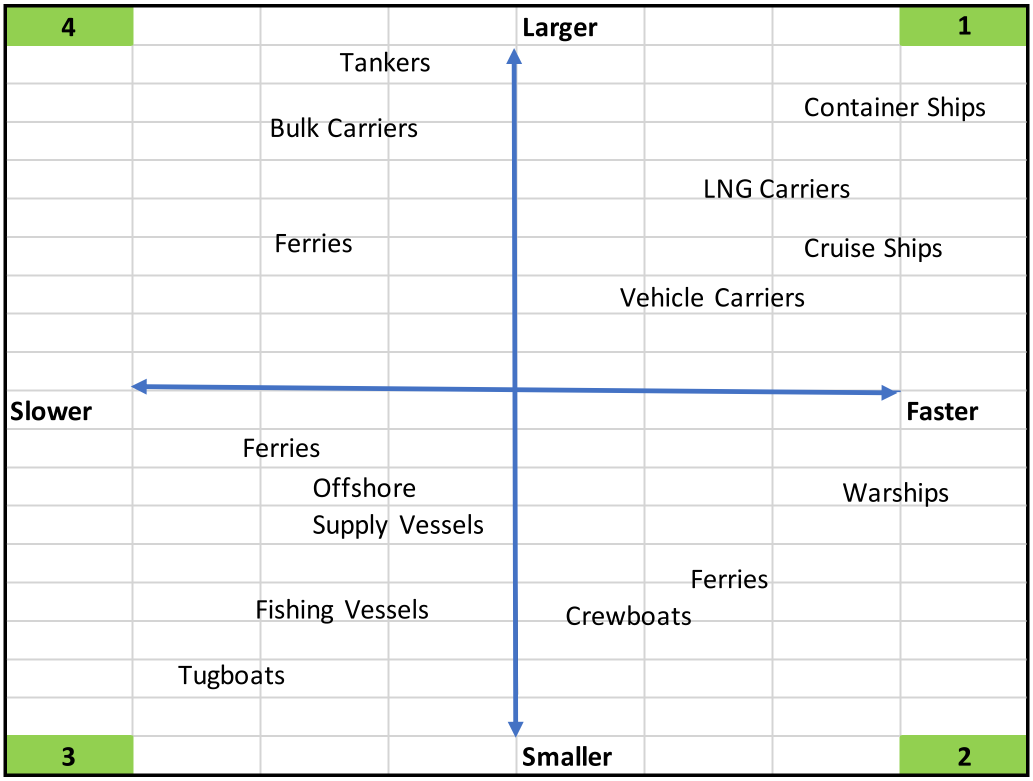


Figure 3: Ship Types

4.9 EFFECTIVENESS (FREQUENCY RANGE, INTENSITY REDUCTION)

Any effective mitigation measure will provide a reduction in radiated energy, which may cover a wide range of frequencies or a narrower band.

There is often some uncertainty, or a considerable range in effectiveness for many measures. “Ideal” values are often not fully achieved in real installations; for example, mounting systems or acoustic enclosures may lose effectiveness due to noise short-circuits through piping, exhaust systems, etc. Propeller treatments may be compromised by minor damage or by marine fouling. The matrix aims to present effectiveness bands that would be expected to be achieved in practice, using the terminology:

Amount of Expected Noise Reduction in Decibels (dB):

- Low (up to 5dB),
- Medium (5-10 dB),
- High (>10dB)

The effectiveness values relate to the noise source being treated, and not necessarily to the overall noise signature of the ship. If propeller noise dominates the URN, then machinery noise reduction treatments will have little or no effect on the overall noise signature.

The frequency ranges treated are linked to the type of noise source and to the treatment approach. Resilient mounts, rafting systems etc. are intended mainly to block the transmission of energy at the characteristic frequencies of the source, such as engine firing rate and harmonics. Cavitation noise reduction has broad spectrum benefits, though it will also address blade rate effects at lower frequencies.

Only a few of the methods listed in the matrix have been explored in sufficient detail to define their URN benefits in typical ship applications. There is an urgent need for more measurement campaigns to provide better definition in this area.

4.10 PREDICTION METHODS

The section of the matrix that addresses prediction methods has fewer columns and uses more descriptions and fewer codes.

Prediction methods have been arranged by area (propeller, machinery noise etc.) and by type. Types consider whether a method is empirical (based on experience and data) or more theoretical. This is not a hard distinction, as most theoretical methods have been tested and calibrated to a greater or lesser extent against data and should not be trusted if they have not been. Where available the notes to each method discuss the extent to which this validation has taken place.

Noise prediction is a specialized area of engineering, and in most cases is undertaken for ship designs by a small number of expert consultancies. These organizations have adapted theoretical acoustic models to allow for their use in practical applications, generally through software with empirical coefficients and correction factors. In some cases, software models of this type are available for purchase, but are not typically very user-friendly and are quite expensive. The matrix provides examples of software products against a number of methodologies, but this list should not be considered as either exhaustive or as an endorsement of the products named.

TRL in this part of the matrix is again used as an indicator of maturity. A number of researchers are known to be working in several of the categories indicated, and so in some areas the TRL shown may not capture most recent developments.

5 ADDITIONAL CONSIDERATIONS

Noise reduction will almost always incur extra cost in design and construction, and often in ship operation. Sometimes the role of the ship will mean that these costs have to be expected; for example, cruise ships, research vessels, and naval applications. Regulations may require reduction in onboard noise for crew habitability, but do not yet apply to underwater noise. Therefore, many owners will be reluctant to apply best practices for URN reduction unless there is some alternative incentive.

Several URN technologies/methodologies will also provide some level of operating efficiency. In fact, as noted in the matrix many have been developed for efficiency reasons, with noise reduction as a side-benefit. This is the case for many propeller efficiency-enhancing measures. Also, some enablers of noise reduction, such as the implementation of electric propulsion, may be adopted for other reasons entirely, such as providing redundancy to gain a dynamic positioning (DP) notation. A relatively modest additional cost may then be all that is needed to gain significant acoustic benefits.

Voluntary, industry-led programs such as Green Ships or Green Marine provide companies with branding benefits to attract environmentally-sensitive clients. In some cases, they offer savings for port fees and services to help offset the costs of environmental impact reduction. Several governments have helped to set up such programs using their own financial and other incentives.

6 SUMMARY

This report introduces URN and summarizes the reasons for concern over the continued increases in noise in the world’s seas and oceans.

It also explains the approach taken in expanding and further developing the matrix of URN reduction approaches and prediction methodologies that are provided in Appendix A below. A wide range of mitigation measures are available to address different types of noise at varying levels of effectiveness. All will incur some level of cost, but in some cases there are co-benefits such as efficiency enhancements that may offset some or all of this disadvantage.

The report is intended to inform future decisions by shipowners, regulators and other stakeholders on investments in research, technology and operational controls.

APPENDIX A – TECHNOLOGY MATRIX

APPENDIX B – CITATION INDEX

Vard Marine Inc.

APPENDIX A - TECHNOLOGY MATRIX

Report 368-000-01

Rev 4

Prepared for

Innovation Centre

Of

Transport Canada

by

Vard Marine Inc.

Date: 12 February 2019

TERMINOLOGY

Advantages/Benefits

CC - Enhanced Crew/passenger Comfort
E - Reduced Emissions
F - Enhanced eFficiency
M - Reduced Maintenance
MA - Increased MAneuverability
S - Decreased Space Demand
W - Decrease in Weight

Disadvantages/Challenges

D - Increased Design effort
E - Increased Emissions
F - Reduced eFficiency
M - Increased Maintenance
MA - Reduction in MAneuverability
P - Increased complexity
S - Increased Space demand
W - Increased Weight

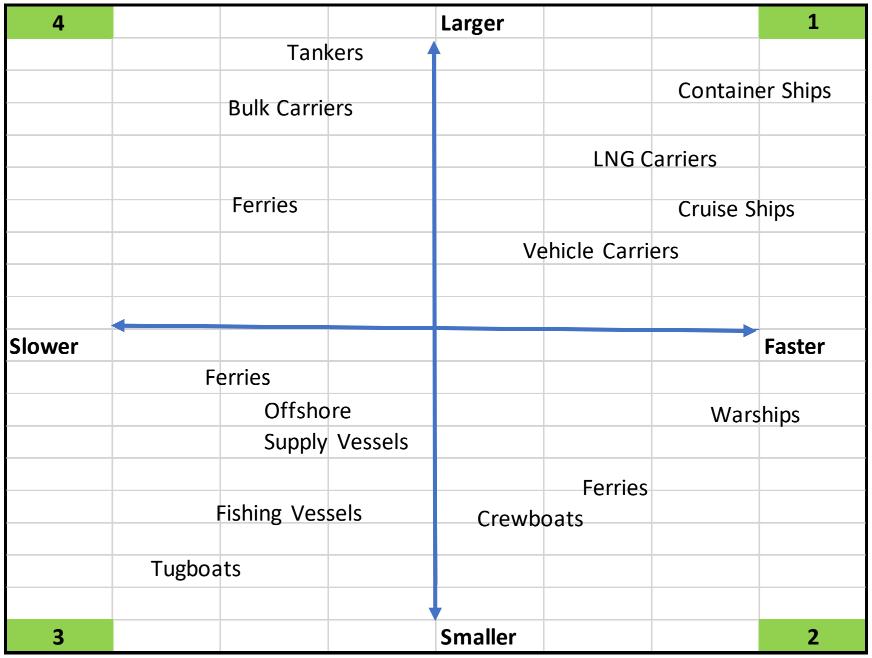
TRL - Technology Readiness Level

Cost Estimation

Range - Range of expected cost
Percentage - Percentage increase or decrease
Payback Period - Time in months/years to recover investment
Shorthand - Whether to expect an increase or decrease

Applicability

ReFit - RF
New Build - NB
Ship Type - By quadrant from Figure, except where indicated.



Effect

Frequency Range - Broadband/Narrowband; Expected Frequency Range Affected in Hertz (Hz)
Noise Reduction - Expected Noise Reduction in Decibels (dB):
Low (up to 5 dB),
Medium (5-10 dB),
High (greater than 10 dB

TECHNOLOGY MATRIX

Treatment/Description	**Advantages/ Benefits**	**Disadvantages/ Challenges**	**TRL**	**Cost Estimation** Percentage/ Range	**Applicability** RF/ NB Ship Types	**Effect** Frequency Range (Hz)	**Effect** Noise Reduction (dB)
1. PROPELLER NOISE							
1.1 PROPELLER/PROPULSOR DESIGN							
1.1.1 Reduction of Turns per Knot (TPK): Reducing the number of propellers turns per knot of speed, thus, reducing the speed of the flow at the tips of the blades. This requires a larger diameter of propeller and is applicable to both fixed and control pitched propellers. Reduces all forms of propeller cavitation (especially propeller tip cavitation) and increases Cavitation Inception Speed (CIS). [1]	**F** **CC**	**D**	**9**	**Unknown**	**NB** **1 - 4**	**ALL**	**Dependent on application – low to medium**
1.1.2 Increased Propeller Immersion: The hydrostatic pressure put forth on the propeller can affect the amount of cavitation that occurs and the CIS. The greater distance the propeller is from the free surface of the sea, the less cavitation will occur and the higher the CIS. Practical design constraints may limit. [2]		**D**	**9**	**Unknown**	**NB** **1 – 2**	**Unknown**	**Low**
1.1.3 High Skew Propeller: Propeller with blades swept back substantially more than conventional propellers. This allows for the blade to pass through the varying wake filed in a more gradual manner, improving the cavitation patterns. Load reduction on the tip of the propeller results in further reduction of propeller cavitation and increased Cavitation Inception Speed (CIS). [3] [4] [5]	**F** **CC** **M**	**D** **F** **W**	**9**	**10-15% Higher capital cost than conventional propellers**	**RF/ NB** **1 - 2**	**40-300**	**Medium,** **depending on initial wake field**
1.1.4 Contracted Loaded Tip Propellers (CLT): Propellers designed with an end plate allowing for maximum load at the propeller tip, which reduces propeller tip cavitation and increases CIS. The end plate also promotes a higher value of thrust per area (higher speed with smaller	**F** **CC**	**D**	**9**	**20% Higher capital cost than conventional propellers**	**RF/ NB** **1 – 4**	**40-300**	**Medium**

Treatment/Description	Advantages/ Benefits	Disadvantages/ Challenges	TRL	Cost Estimation Percentage/ Range	Applicability RF/ NB Ship Types	Effect Frequency Range (Hz)	Effect Noise Reduction (dB)
optimum diameter) further reducing noise, vibrations and further increasing Cavitation Inception Speed (CIS). [5] [6] [7]							
1.1.5 Contra-rotating Propellers: Co-axial propellers, one propeller rotating clockwise & the other rotating counter clockwise. Increases CIS due to reduction in blade loading resulting in lower blade surface cavitation. Also, optimised flow circulation results in lower tip vortex cavitation. [8] [9]	**F**	**D** **M** **P**	**9**	**Much higher capital cost than conventional propellers**	**RF/ NB** **1 – 2**	**40-300**	**Low to medium**
1.1.6 Kappel Propellers: Propeller blades modified with tips curved towards the suction side. This reduces the strength of the tip vortex thus increasing efficiency, decreasing tip vortex cavitation, and increasing CIS. [10] [11]	**F**	**D**	**9**	**20% higher capital cost than conventional propellers [5]**	**RF/ NB** **1 – 2**	**40-300**	**Low**
1.1.7 Propeller with Backward Tip Raked Fin: Propeller modified in such a way the blades are curved towards the Pressure side (Opposite of Kappel Propellers), Studies have shown that there is an increase in efficiency and decrease in cavitation expected, however, there are few studies on the subject. [12]	**F**	**D**	**6** **9**	**Higher capital cost than conventional propellers**	**RF/ NB** **1 - 2**	**Unknown**	**Unknown** **(Improves wake flow)**
1.1.8 Podded Propulsors: This type of propulsion achieves improved wake performance to the propeller reducing cavitation and CIS. However, the drive configuration can increase medium to high frequency noise; see also 2.2.1 (Enabled by Diesel electric design) [13] [14]	**CC** **MA**	**D** **P** **F**	**9**	**Power dependent; typically 25% more than shafted system**	**NB** **1 – 4**	**Unknown**	**Low to Medium**
1.1.9 Water Jets: Operate in ducting internal to the ship, with increased pressures at the jet. Noise reduction from higher cavitation inception speed and by isolating the propeller from the sea. [14] [15] [16]	**F (high speed)** **high power density for fast, shallow draft vessels**	**F (at low speeds)** **M** **P** **W**	**9**	**Higher than conventional propeller and shafting; higher installation cost**	**NB** **2** **Highest speeds and some speciality types**	**All**	**High**

Treatment/Description	**Advantages/ Benefits**	**Disadvantages/ Challenges**	**TRL**	**Cost Estimation** Percentage/ Range	**Applicability** RF/ NB Ship Types	**Effect** Frequency Range (Hz)	**Effect** Noise Reduction (dB)
1.1.10 Pump Jets: Combine a full pre-swirl stator, propeller and duct. Used in ultra-quiet applications such as submarines. [17]		**F** **M** **P** **W**	**7** (for conventional ships)	**Higher cost than conventional prop**	**NB** **2**	**All**	**High**
1.1.11 Composite Propellers: Use of advanced composites to allow for blade (tip) distortion under load to delay cavitation onset and reduce blade vibration.	**CC** **W**	**D**	**6**	**Unknown at this time**	**NB/RF** **2, 3**	**All**	**Low**
1.2 WAKE FLOW MODIFICATION							
1.2.1 Pre-swirl Stator: Consists of Stator blades located on the stern boss in front of the propeller, flow is redirected before entering the propeller, increasing over all flow performance, thus reducing cavitation and increases CIS. [17]	**E** **F**	**D**	**9**	**Typical Payback Period: 24 months**	**RF/ NB** **4**	**All**	**Low**
1.2.2 Schneekluth Duct: An oval shaped duct located just forward of the upper half of the propeller, designed to improve the flow to the upper part of the propeller, this improves flow performance, lowering the formation of cavitation of propeller blade tips and increasing CIS. [18] [19]	**E-** **F**	**D**	**9**	**Typical** **Payback Period: 4 months**	**RF/NB** **1, 4**	**All**	**Low**
1.2.3 Propeller Boss Cap Fin (PBCF): Small fins attached to the hub of the propeller, reducing hub vortex cavitation, thus, reducing noise and vibration and increasing CIS. The design also recovers lost rotational energy, increasing efficiency. Similar concepts include ECO-CAP [19] [20]	**E** **F**	**D**	**9**	**Typical Payback Period:** **4 – 6 months** **[21]**	**RF/NB** **1, 4**	**≤ 1.0kHz**	**Medium**
1.2.4 Propeller Cap Turbines (PCT): Hydrofoil shaped blades integrated into the hub cap, similarly to PBCF reducing hub vortex cavitation, and increasing CIS. The design also recovers lost rotational energy, increasing efficiency. [19] [20]	**E** **F**	**D**	**9**	**Typical Payback Period:** **4 – 6 months** **[22]**	**RF/NB** **1, 2, 4**	**≤ 1.0kHz**	**Medium**

Treatment/Description	Advantages/ Benefits	Disadvantages/ Challenges	TRL	Cost Estimation Percentage/ Range	Applicability RF/ NB Ship Types	Effect Frequency Range (Hz)	Effect Noise Reduction (dB)
1.2.5 Grothues Spoilers A small series of curved fins attached to the hull forward of the propeller, designed to improve flow to the propeller, reducing cavitation, increasing CIS and increasing fuel efficiency. [18]	**E** **F**	**D**	**9**	**Typical Payback period:** **Less than a year**	**RF/NB** **1, 4**	**Unknown**	**Low**
1.2.6 Mewis Duct A combination of a duct with pre-swirl stators integrated into the duct just forward of the propeller, thus having the benefits of both pre-swirl stators and grothues spoiler. Similar concepts include Super Stream Duct [5] [23]	**E** **F**	**D**	**9**	**Typical Payback Period:** **Less than a year**	**RF/NB** **1, 4**	**Unknown**	**Low**
1.2.7 Promas: Integration of the propeller, hubcap, rudder bulb, and rudder into one hydrodynamic efficient unit. Reduces propeller tip loading and limiting blade pressure pulses, thus, reducing cavitation and CIS. Similar concepts include Ultimate Rudder Bulb and SURF BULB[24]	**F** **E**	**D**	**9**	**Typical Payback Period: less than 2 years**	**NB** **1, 2**	**Unknown**	**Low to Medium (depending on initial flow)**
1.2.8 Costa Propulsion Bulb (CPB): Consists of two bulb halves that are welded to the rudder, in line with the propeller. Designed to recover energy losses aft of the propeller, by eliminating vortices caused by cavitation, ultimately reducing propeller vibrations and lowering URN. [25]	**F**	**D**	**9**	**Payback Period:** **4 – 15 years** **[22]**	**NB/ RF** **1, 2**	**Unknown**	**Low**
1.2.9 Twisted Rudder: Rudder designed to twist in order to vary the angle of attack to match water flow pattern. This reduces all cavitation and increases CIS. Used on a variety of vessels, including BC Ferries and U.S Navy Destroyers. [26]	**M** **F** **MA**	**D**	**9**	**Payback Period:** **4 – 15 years** **[22]**	**NB/ RF** **1, 2**	**Unknown**	**Low**
1.2.10 Asymmetric Body for Single Screw Vessels The purpose of designing an asymmetric after body is to account for the asymmetrical flow of a single screw propeller about the centerline. This will slightly increase CIS. [27] [3]	**F**	**D**	**9**	**Unknown**	**NB** **1, 4**	**Unknown**	**Low**

Treatment/Description	Advantages/ Benefits	Disadvantages/ Challenges	TRL	Cost Estimation Percentage/ Range	Applicability RF/ NB Ship Types	Effect Frequency Range (Hz)	Effect Noise Reduction (dB)
1.2.11 CPP Combinator Optimization Adjusting pitch and rpm settings for controllable pitch propellers can mitigate the early onset of cavitation on pressure and suction sides both at constant speeds and during acceleration. This may also improve propeller efficiency in these conditions [77]	**F**	**D**	**8**	**Modest, requires software updates and potentially additional sensors**	**NB/RF** **All**	**All**	**Medium**
1.3 SUPPLEMENTARY TREATMENTS							
1.3.1 Improved Manufacturing Processes: Tighter tolerances on blade manufacture may reduce cavitation. [28]	**F**	**D**	**9**	**10+% more expensive than standard propeller**	**NB/RF** **1 - 4**	**Unknown**	**Low**
1.3.2 Air Bubbler System (Prairie): Air injection through holes in the propeller blade tips, this fills the vacuum left by the cavitation as propellers rotate, allowing cavitation bubbles to contract more slowly as area that is under pressured is minimised. Reducing cavitation and increasing CIS. Must be used while docked as well to reduce marine growth clogging holes. Used by navies to reduce noise for stealth purposes. [29]		**D** **F** **M**	**6 (in commercial application)**	**20000 – 75000 +**	**NB** **1, 2**	**20 – 80** **500+**	**Medium**
1.3.3 Propeller Blade maintenance Imperfections of a propeller blade can encourage cavitation. Polishing between dry docks can prevent this, reducing cavitation and increasing CIS. [30]	**F**	**M**	**9**	**Unknown**	**RF** **1 - 4**	**All**	**Low**
1.3.4 Anti-Fouling Coating: A coating applied to the surface of a propeller with the purpose of reducing propeller fouling. Research has been done regarding underwater noise with varying results. [31]	**M**		**9**	**Payback Period:** **2 years** **[22]**	**NB/RF** **All**	**50 -10000Hz**	**Low**

Treatment/Description	**Advantages/ Benefits**	**Disadvantages/ Challenges**	**TRL**	**Cost Estimation** Percentage/ Range	**Applicability** RF/ NB Ship Types	**Effect** Frequency Range (Hz)	**Effect** Noise Reduction (dB)
1.3.5 Application of Anti-Singing Edge: Modification to the propellers trailing edge, designed to alter naturally occurring vortex shedding phenomenon. [32] [33]			**9**	**Increase in manufacture cost**	**NB/RF** **1 - 4**	**10 – 12000**	**High (where singing is a problem)**
2.0 MACHINERY							
2.1 Machinery Selection							
2.1.1 Prime Mover Selection The choice of prime mover (main engines) has a strong influence on the basic machinery noise characteristics of the ship and on the potential use of mitigation measures. Diesels are currently the default choice of prime mover for almost all commercial vessels and so are assumed here except where otherwise indicated. See main report for additional discussion.							
2.1.2 (Diesel) Electric: Using electric rather than mechanical transmission enables and/or facilitates many noise reduction approaches, from the use of mounts and enclosures to active noise cancellation. A wider range of propulsor selections are also available. Electrical transmission has worse efficiency than mechanical, and capital costs are higher so use is generally in vessels where other benefits outweigh these costs. [34]	**MA (paired with azimuth thrusters)** **S** **W**	**F**	**9**	**Highly variable**	**NB** **Most applicable to vessels that have widely varying speeds in operational profile, and/or redundancy requirements for dynamic positioning, etc**	**ALL**	**High**
2.1.3 Gas/Steam Turbine Rotating turbines are generally quieter than diesels but have lower fuel efficiency and higher capital cost. Very few steam ships are now constructed (other than for nuclear vessels) but many naval vessels use gas turbines for high power density. [35]	**S** **CC** **E (compared to Diesel)**	**F** **D** **M** **P**	**9**	**Much higher capital cost than diesel**	**NB** **1, 2**	**ALL**	**High**

Treatment/Description	**Advantages/ Benefits**	**Disadvantages/ Challenges**	**TRL**	**Cost Estimation** Percentage/ Range	**Applicability** RF/ NB Ship Types	**Effect** Frequency Range (Hz)	**Effect** Noise Reduction (dB)
2.1.4 Stirling Engine: The external combustion stirling engine produces lower noise then conventional internal combustion engines. Load following characteristics are relatively poor, so difficult to have rapid variations of power. Main uses are for submarines and naval vessels to reduce radiated noise. [36]	**F** **E** **(multiple fuel capability)** **M**	**W** **S**	**6**	**High capital cost**	**NB**	**Unknown**	**Medium**
2.1.5 Azimuthing Propulsors Azimuthing propulsors may have motors inside the hull with transmission gears (electro-mechanical) or outside the hull in a propeller fairing (fully electric). Either type can have propulsor noise benefits as noted in 1.1.8. Electro-mechanical types may have gear noise to mitigate while fully electric have electric motor noise. Limited public domain information is available on the machinery noise characteristics of either type though both claim excellent performance. [13] [14]	**F (compared to conventional diesel electric)** **MA** **W** **CC**	**F (compared to conventional diesel)**	**9**	**Power dependent; typically 25% more than shafted system**	**NB** **1, 2, 3**	**Unknown**	**Unknown**
2.2 Machinery Treatments							
2.2.1 Resilient Mounts (Equipment): Spring mounts impede the transmission of vibration energy from machinery, and the generation of energy into the water from the hull. Requires appropriate selection and installation of mounts. Not generally practical for heavy 2-speed diesels. [37]	**CC**	**S** **W**	**9**	**20 – 2000$ per mount; large engines require many mounts and installation cost,**	**NB/ RF** **2, 3**	**All**	**High, best at higher frequencies**
2.2.2 Floating Floor (Deck): A Floating/False deck is constructed and resiliently mounted to the deck, effectively isolating all machinery on the false deck; applicable to lighter equipment only. [37]	**CC**	**S** **W**	**9**	**Unknown**	**NB/ RF** **All**	**All**	**Low, main benefits internal**

Treatment/Description	**Advantages/ Benefits**	**Disadvantages/ Challenges**	**TRL**	**Cost Estimation** Percentage/ Range	**Applicability** RF/ NB Ship Types	**Effect** Frequency Range (Hz)	**Effect** Noise Reduction (dB)
2.2.3 Raft Foundation (Double stage vibration isolation system) One or several pieces of machinery are mounted on an upper layer of mounts supported by a raft (steel structure) which is further supported on the hull girder on a lower level set of mounts. This reduces noise by creating an extra impedance barrier to the transmission of vibration energy. Often used for engine/gearbox or engine/generator; not applicable to 2-stroke diesels due to high weight. [38]	**CC**	**W** **D** **S**	**9**	**Adds significantly to installation cost; can be 10%+ of cost of installed equipment**	**NB/ RF** **2, 3**	**All**	**High, best at higher frequencies**
2.2.4 Acoustic Enclosures: Structures designed to enclose a specific piece of machinery, absorbing airborne noise. This reduces the airborne transmission of energy to the hull and the generation of URN from the hull. [39]. Typically used only with smaller diesels and gas turbines.	**CC**	**S** **D**	**9**	**Adds significantly to installation cost; can be 10%+ of cost of installed equipment**	**RF/ NB** **2, 3** **Used on vessels requiring very low noise signatures such as warships, research vessels after treatment of other noise paths.**	**125 – 500**	**High**
2.2.5 Active Cancellation: Reduction of machinery excitation of the hull structure by means of secondary excitation to cancel the original excitation. Uses sensors for measuring excitation, a device to read the sensor and actuators to produce counter phase excitation. Capital cost is high. [40]	**CC**	**S** **D**	**6**	**Highly variable**	**NB**	**Effective at tuned frequencies**	**High** **Effective for discrete frequencies rather than overall noise levels**
2.2.6 Spur/Helical Gear Noise Reduction Gear design can be used to optimize number of teeth & profile shift angle. This will optimize sound reduction due to teeth mashing lowering machinery noise. Also requires high quality manufacturing [41] [42]	**F** **M**	**D**	**9**	**Increase in manufacture cost, can double gear cost (milspec)**	**NB**	**Effective mainly at gear meshing frequencies**	**Medium/ High**

Treatment/Description	**Advantages/ Benefits**	**Disadvantages/ Challenges**	**TRL**	**Cost Estimation** Percentage/ Range	**Applicability** RF/ NB Ship Types	**Effect** Frequency Range (Hz)	**Effect** Noise Reduction (dB)
2.2.7 Control of Flow Exhaust gases (Enabled by 2-stroke diesel Engine) Exhaust flow component designed to reduce noise produced by sudden gas expansion during the combustion/exhaust stroke of a 2-stroke diesel engine. [43]	**F**	**D**	**3**	**Unknown**	**NB** **1, 4**	**Unknown**	**Low**
2.2.8 Metallic Foam A porous material designed to be used in the tanks of diesel or water ballast tanks, to reduce underwater radiated noise. The material has open enhanced acoustical properties when saturated by liquids [44]	**CC**	**N/A**	**6**	**Unknown**	**Unknown**	**Unknown**	**Unknown, claimed as High**
2.2.9 Structural (Hull/Girder/Floor Thickening) The thickness of structural members are directly linked to URN mitigation. Rigid structure creates impedance mismatch and is particularly effective used with resilient mounts; added weight is also useful for noise transmission reduction [45]	**CC**	**D** **S** **W** **F**	**9**	**Unknown**	**NB** **2, 3**	**10 – 1000**	**Medium**
2.2.10 Structural Damping Tiles The application of dampening tiles integrated into the structure of a vessel, absorbing vibration energy, resulting in a reduction of URN. [45]	**CC**	**W** **D**	**9**	**$50 – 150 per m^2**	**NB/RF** **2, 3**	**200+**	**High if treatment is extensive, best at higher frequencies**
2.2.11 Acoustic Decoupling Coating Layer of rubber foam or polyethylene foam applied to the exterior of the vessels hull, designed to decrease noise radiation from machinery vibration energy. (most commonly applied to submarines) [46]	**F**	**M** **(Hard to control corrosion between tiles & hull)**	**7**	**$250 – $1000 per m^2 plus engineering design and installation costs**	**NB/RF** **2, 3**	**800+** **100 – 800**	**Unknown, claimed as High forhigher frequencies**

Treatment/Description	**Advantages/ Benefits**	**Disadvantages/ Challenges**	**TRL**	**Cost Estimation** Percentage/ Range	**Applicability** RF/ NB Ship Types	**Effect** Frequency Range (Hz)	**Effect** Noise Reduction (dB)
2.3 Alternative fuel selection							
2.3.1 Fuel Cell Produces electricity through chemical reaction, this is done by converting hydrogen and oxygen to water. Significantly quieter than any combustion engine. (The efficiency of fuel cells themselves are quite high however, when infrastructure & storage is taken into account compared to diesel or other methods, the efficiency decreases significantly) [47] [48] [49]	**CC** **E** **W** **F**	**D** **P** **S**	**7**	**High capital cost** **Increase in fuel cost**	**NB**	**All**	**High**
2.3.2 Battery (Stored electrical energy, also supercapacitors) Draws on stored energy provided by shore power or from integrated electric power plant on ship. Batteries themselves are inherently silent removing all prime mover noise when in use. Low energy density means can only be used for short voyages, or for portions of longer voyages in (e.g.) noise-sensitive areas. [50]	**E** **F**	**S** **W**	**9**	**High capital cost**	**NB/RF** **2, 3** **Applicable to vessels with short routes or highly varying speed profiles**	**All**	**High**
3.0 Hydrodynamic							
3.1 Hull Treatments							
3.1.1 Underwater Hull Surface Maintenance Poor hull surface maintenance can lead to resistance increases. This can cause the machinery load on machinery to increase and propeller RPM to travel at the same speeds, thus increasing URN. Hull surface maintenance must be completed regularly to avoid this. [51]	**F** **E**	**M**	**9**	**Hull polishing cost depends on ship size**	**RF** **All**	**All**	**Low**
3.1.2 Air Bubbler System (Masker): Air injection around the hull of the vessel to reduce noise created by machinery, creates a blanket of air bubbles	**F**	**M**	**7 (in comme**	**20000 – 75000 +**	**NB**	**20-80**	**High [78]**

Treatment/Description	**Advantages/ Benefits**	**Disadvantages/ Challenges**	**TRL**	**Cost Estimation** Percentage/ Range	**Applicability** RF/ NB Ship Types	**Effect** Frequency Range (Hz)	**Effect** Noise Reduction (dB)
between the machinery noise and water, and uses tubing systems and an air compressor. Also has the effect of highly reducing marine growth on the hull, improving overall efficiency. Must be used while docked as well to reduce marine growth clogging tubing holes. Used by navies to reduce noise for detection stealth purposes. [29]		**D**	**rcial ships)**	**Payback Period:** **4 – 15 years** **[22]**	**1, 2, 3**	**500+**	
3.1.3 Hull Air Lubrication: Air lubrication systems (ALS) have been introduced by several shipbuilders to reduce skin friction resistance for power savings [80], [83]. It is probable that this will have similar effects to Masker systems on naval vessels.	**F**	**D** **M**	**8**	**Similar to 3.1.2**	**NB** **1, 2**		**High**
3.2 Hull Appendage/Design							
3.2.1 Efficient Hull Forms Hydrodynamically efficient hull forms will reduce power requirements and therefore both machinery and propulsor noise. Such hulls will also generally have good wake characteristics, increasing cavitation inception speeds. [52]	**F**	**D**	**9**	**Unknown**	**NB** **All**	**ALL**	**Application dependent**
3.2.2 Stern Flap/Wedge Small extensions from the lower transom. Modifies the stern wave produced by the vessel and reduces powering requirements, reducing hydrodynamic noise. Similar benefits will come from other stern flow modification appendages, such as hull vanes and interceptors. [53] [54]	**F** **E**	**D**	**9**	**Unknown**	**NB/ RF** **1, 2**	**ALL**	**Low**
4.0 Other Mitigation Technologies							
4.1 Wind							
4.1.1 Kite Sails Kites attached to the bow of a Merchant/commercial vessel, designed to create thrust that replaces power from conventional machinery and propeller thrust. [56]	**F** **E**	**D**	**8**	**Payback Period:** **15+years** **[22]**	**NB/ RF** **1, 4** **Not suited to smaller vessels**	**ALL**	**Medium to High** **(Depending on speed reduction and primary**

Treatment/Description	**Advantages/ Benefits**	**Disadvantages/ Challenges**	**TRL**	**Cost Estimation** Percentage/ Range	**Applicability** RF/ NB Ship Types	**Effect** Frequency Range (Hz)	**Effect** Noise Reduction (dB)
					or to operations on short routes and fixed schedules, e.g. smaller ferries		**propulsion source)**
4.1.2 Flettner/Magnus Rotors Tall, smooth, rotating cylinders with an end plate at the top. Extruding from the main deck of the vessel. An external force with wind causes rotation creating thrust that replaces power from conventional machinery and propeller thrust. Similar to conventional sails in URN reduction. [57]	**F**	**D** **S** **P**	**8**	**Payback Period:** **15+years** **[22]**	**NB/ RF** **1, 4** **Not suited to smaller vessels or to operations on short routes and fixed schedules, e.g. smaller ferries**	**ALL**	**Medium to High** **(Depending on speed reduction and primary propulsion source)**
4.1.3 Conventional Sails As with kites and rotors, any form of sail assist can reduce machinery power requirements and propeller noise.	**F**	**D** **S** **P**	**9**	**Dependent on vessel and installation**	**NB** **3, 4** **Not suited to operations on short routes and fixed schedules, e.g. smaller ferries**	**ALL**	**Medium to High** **(Depending on speed reduction and primary propulsion source)**
4.1.4 Cold Ironing (Shore Power) Provision of higher power shore supplies to large vessels (cruise ships, containers ships) can allow these vessels to turn off all generating equipment while in port, lowering URN while alongside. [81]	**E** **F** **M**	**S** **W**	**9**	**$1.5 m per berth, $400k per vessel**	**NB/RF** **1** **Also often used for smaller vessels with standard home ports**	**<1000**	**Medium**

Predicting URN				
Prediction Method	**Description**	**Comments**	**Software/Vendors (examples)**	**TRL**
1.0 Computational				
1.1 Propeller				
Empirical; e.g. Tip Vortex Cavitation Method	An approximate method based on numerical and experimental data. It is generally considered that tip cavitation produces the predominant noise produced by cavitation followed by sheet cavitation. [58], [84]	Semi-empirical methods require detailed knowledge on the appropriate empirical input parameters to be used which need to be scaled to the results of model or full scale tests. Uncertainty levels can be high.	Used by DNV and others for noise prediction	**9**
Semi-empirical, e.g. Lifting Surface method\potential flow	Propeller Blades are analyzed as lifting surfaces over which singularities such as the vortex are distributed over the surface to model the effects of blade loading/thickness. [65] [66] [67]. To perform this method detailed propeller geometry & wake distribution must be provided, pressure distribution calculations must be performed to produce lifting surfaces from the blade geometry. From here determination of sheet cavitation regions can take place, than calculations of sheet cavitation swept area can occur. This can then be converted to broad band noise levels using a conversion equation such a Brown's Formula [68], [88]	Incompressible flow methods such as lifting surface cannot capture viscous flow features such as boundary layers and vortices and have difficulty in modelling cavitation accurately.	PUF PROPCAV PROCAL	**8**
Computational Fluid Dynamics	Tip Vortex cavitation can be predicted in many different ways using CFD. [58] The Reynolds stress turbulence model may be used for computation of propeller flow using FLUENT [59], transition-sensitive eddy-viscosity turbulence model to resolve the boundary transition layer effects [60], Commercial Reynolds Averaged Navier Stokes (RANS) solvers [61] [62], RANS solvers need to be paired with other methods to change the form of data calculated for example Detached-Eddy Simulations (DES) paired with the Spalart-Allmaras eddy viscosity model [63] or Direct Navier-Stokes simulations [64]. Conversion of tip vortex intensity into URN levels for high frequencies in particular requires similar approached to Lifting Surface methods using Brown's Formula or others as direct capture of tip vortex cavitation is difficult [89]	RANS codes consider viscous flow features in a more simplified way than LES (large eddy simulation) codes, giving lower accuracy in some cases but with less computational effort. None of these methods can be used other than by highly specialized personnel.	OpenFoam (Simple Foam RANS Solver) ANSYS (FLUENT) Star CCM+ ANSYS CFX ReFRESCO	**7**
1.2 Machinery				
Empirical **[69]**	Empirical formulae have been derived for many airborne, duct-borne and structure-borne noise transmission paths, and can be combined into overall prediction methodologies.	These methodologies are mainly concerned with internal noise and require manipulation to be used for URN prediction.	DNVGL in-house software CABINS software from TNO	**9**

Predicting URN				
Prediction Method	**Description**	**Comments**	**Software/Vendors (examples)**	**TRL**
Semi-empirical: Statistical Energy Analysis (SEA) **[70]** **[71]**	SEA uses energy flow relationships to calculate the diffusion of acoustic and vibration energy through a structure before its propagation into the water. In the SEA method, a complex structure is considered as a system formed of coupled subsystems. Each subsystem represents a group of modes with similar characteristics and a storage of energy. SEA predicts the average response of the structure, reducing the amount of calculation required.	SEA methods are still reliant on empirical data for calibration, and the accuracy of predictions can be less than for empirical. Only specialized personnel can use method reliably.	Designer-NOISE (Noise Control Engineering) SEAM (Cambridge Collaborative) Deltamarine	~~9~~ ~~**8**~~
Full Frequency Range Vibro-Acoustic Prediction	Utilizes statistical energy analysis (SEA), structural and acoustic finite element (FE), and boundary element (BE) solvers alone and combined in hybrid models for vibroacoustic response to machinery, flow-related and hydroacoustic inputs. FE and BE are used for low frequency ship response and URN prediction, hybrid FE/BE/SEA for higher frequency predictions, and SEA for high frequency predictions. Measured and empirical information can be incorporated as user-defined properties/characteristics.	The advanced SEA algorithms in these methods do not rely on empirical data. Considerable expertise in structural-acoustics is required to use these methods	VAOne (ESI Group) Wave6 (Dassault Systemes)	
Low Frequency Noise Prediction/Finite Element Methods **[72]**	The purpose of this method is to calculate URN caused by machinery noise similarly to the SEA method. The method requires a 3D CAD model converted to a Finite Element model. Various loads and analyses can take place to acquire results for radiated noise analysis. From here a wetted surface FE model and a Boundary Element (BE) code can be coupled to predict low Frequency URN		FE Software (similar to Ansys) Boundary element based code (Ex: AVAST)	**8**
1.3 Entirety				
Noise propagation modeling **[85], [86], [87]**	- Various models can be accessed from the websites listed in the references using methods including parabolic equation, ray trace, normal modes and spectral integration. Some commercial codes have also been developed.	All methods can only be exercised by specialized personnel.	RAM KRAKEN OASES dBSea [73]	**9**
2.0 Model Scale				
Propeller cavitation tunnel	Cavitation tunnels model the propeller and in some cases the hull form immediately ahead of the propeller, reducing the pressure in the tunnel in accordance with scaling laws. Results predict cavitation inception speeds and the development of cavitation patterns. Tunnel tests can also be used to predict pressure pulses & cavitation noise.	Model scale cavitation testing has challenges for replication of wake field, blockage effects and others. Noise measurements are influenced by reverberation from tank walls, background noise and uncertain scaling laws. Open literature available regarding radiated noise full scale and	Approximately 20 commercial model testing facilities have cavitation tunnels. Large scale tunnels are preferable to	**9**

Predicting URN				
Prediction Method	**Description**	**Comments**	**Software/Vendors (examples)**	**TRL**
	Noise levels from the model propeller are extrapolated to full scale using a variety of scaling rules. [78], [79]	model scale comparison and extrapolation can be found in [76].	reduce scaling uncertainties. [74]	
Ship cavitation tank	Cavitation tanks extend the tunnel modelling approach by using whole ship models in a depressurized chamber. This allows for the creation of more accurate wake fields and flow patterns both upstream and downstream of the propeller, giving a more accurate prediction of cavitation. [76], [77]	While some modelling issues are improved compared to cavitation tunnel others become more challenging.	Only two depressurized tanks are in operation, in China and the Netherlands [75]	**9**

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