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ANY OTHER BUSINESS

Ship underwater radiated noise technical report and matrix

Submitted by Canada

SUMMARY

Executive summary:	This document highlights the results of a recent review of underwater radiated noise mitigation measures from ships. These options are presented as a matrix, focussing on new builds and retrofit technologies.
Strategic direction, if applicable:	4
Output:	Not applicable
Action to be taken:	Paragraph 4
Related documents:	MEPC 71/16/5; MEPC 72/16/5; MEPC 73/18/4, MEPC 73/INF.23; MEPC 74/17/2 and MEPC 74/INF.36

1 In order to further understanding and develop measures surrounding underwater radiated noise (URN) from ships, Canada commissioned Vard Marine, Inc. (a Fincantieri Company) to prepare a report that reviews the means of mitigating and predicting the URN from ships. The main outcome of the report is a technical matrix of options and aspects, which can be used as a stand-alone summary of URN reduction measures applicable now and in the future.

2 Attached in the annex are key excerpts from the report, including the executive summary, the URN matrix, and citations.

3 IMO Member States, intergovernmental, and non-governmental organizations interested in reviewing the full report, which includes a summary of URN sources and its effects on marine life, as well as the methodology for the matrix, can request a copy through Transport Canada at: TC.QuietShips-Naviressilencieux.TC@tc.gc.ca.

Action requested of the Committee

4 The Committee is invited to note the information provided in this document.

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ANNEX

EXCERPTS FROM THE REPORT "SHIP UNDERWATER RADIATED NOISE", PREPARED BY VARD MARINE INC FOR TRANSPORT CANADA (FEBRUARY 2019)

Executive Summary

1 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.

2 The main outcome of the work undertaken is a matrix of URN mitigation measures, presented as appendix 1 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.

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

.1 advantages and benefits to the ship's design and operations;

.2 disadvantages and challenges;

.3 technology readiness;

.4 cost impacts for implementation and operation;

.5 applicability to different ship types; and

.6 effectiveness; in terms of frequency ranges and reduction in sound levels.

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

5 Entries in the matrix are supported by citations, and a full list of references is provided in appendix 2 to the report.

6 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.

APPENDIX 1

MATRIX OF URN MITIGATION MEASURES

Underwater Radiated Noise Matrix 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

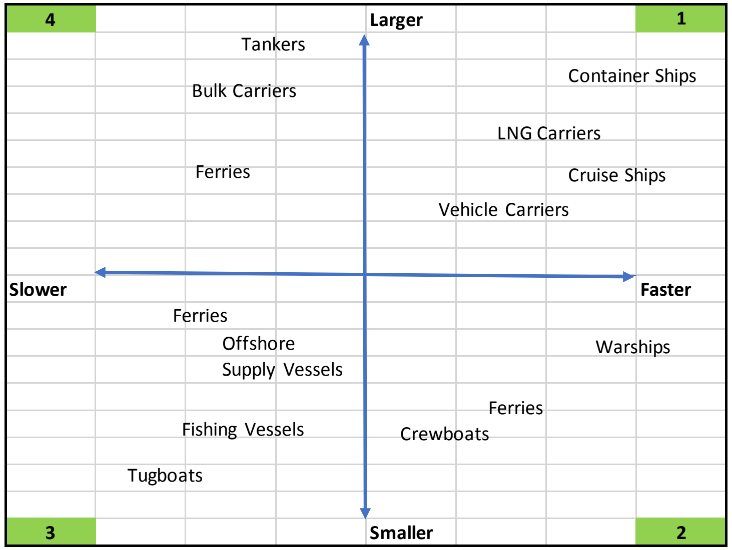
Cost Estimation

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

Technology Matrix

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)

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 optimum diameter) further reducing noise, vibrations and further increasing Cavitation Inception Speed (CIS). [5] [6] [7]	**F** **CC**	**D**	**9**	**20% Higher capital cost than conventional propellers**	**RF/ NB** **1 – 4**	**40-300**	**Medium**
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**

Treatment/Description	**Advantages/Benefits**	**Disadvantages/Challenges**	**TRL**	**Cost Estimation** Percentage/ Range	**Applicability** RF/ NB Ship Types	**Effect** Frequency Range (Hz)	**Effect** Noise Reduction (dB)
1.1.6 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**
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**

Treatment/Description	**Advantages/Benefits**	**Disadvantages/Challenges**	**TRL**	**Cost Estimation** Percentage/ Range	**Applicability** RF/ NB Ship Types	**Effect** Frequency Range (Hz)	**Effect** Noise Reduction (dB)
1.2.2 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**
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**

Treatment/Description	**Advantages/Benefits**	**Disadvantages/Challenges**	**TRL**	**Cost Estimation** Percentage/ Range	**Applicability** RF/ NB Ship Types	**Effect** Frequency Range (Hz)	**Effect** Noise Reduction (dB)
1.2.10 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**
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**
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)**

Treatment/Description	**Advantages/Benefits**	**Disadvantages/Challenges**	**TRL**	**Cost Estimation** Percentage/ Range	**Applicability** RF/ NB Ship Types	**Effect** Frequency Range (Hz)	**Effect** Noise Reduction (dB)
2.0 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**
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	**F (compared to**	**F (compared to**	**9**	**Power dependent; typically 25%**	**NB** **1, 2, 3**	**Unknown**	**Unknown**

Treatment/Description	**Advantages/Benefits**	**Disadvantages/Challenges**	**TRL**	**Cost Estimation** Percentage/ Range	**Applicability** RF/ NB Ship Types	**Effect** Frequency Range (Hz)	**Effect** Noise Reduction (dB)
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]	**conventional diesel electric)** **MA** **W** **CC**	**conventional diesel)**		**more than shafted system**			
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**
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**	**125 – 500**	**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)
					other noise paths.		
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**
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)	**F**	**M (Hard to control corrosion**	**7**	**$250 – $1000 per m^2 plus engineering design and installation costs**	**NB/RF** **2, 3**	**800+** **100 – 800**	**Unknown, claimed as High for higher 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)
[46]		**between tiles & hull)**					
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 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]	**F**	**M D**	**7 (in commercial ships)**	**20000 – 75000 + Payback Period: 4 – 15 years [22]**	**NB 1, 2, 3**	**20-80 500+**	**High [78]**
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**

Treatment/Description	**Advantages/Benefits**	**Disadvantages/Challenges**	**TRL**	**Cost Estimation** Percentage/ Range	**Applicability** RF/ NB Ship Types	**Effect** Frequency Range (Hz)	**Effect** Noise Reduction (dB)
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 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)**
4.1.2 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)**

Treatment/Description	**Advantages/Benefits**	**Disadvantages/Challenges**	**TRL**	**Cost Estimation** Percentage/ Range	**Applicability** RF/ NB Ship Types	**Effect** Frequency Range (Hz)	**Effect** Noise Reduction (dB)
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 analysed 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**
Semi-empirical: Statistical Energy Analysis (SEA) [70]	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	SEA methods are still reliant on empirical data for calibration, and the accuracy of predictions can be less than for empirical. Only	Designer-NOISE (Noise Control Engineering)	~~**9**~~ ~~**8**~~

Predicting URN				
Prediction Method	**Description**	**Comments**	**Software/Vendors (examples)**	**TRL**
[71]	similar characteristics and a storage of energy. SEA predicts the average response of the structure, reducing the amount of calculation required.	specialized personnel can use method reliably.	SEAM (Cambridge Collaborative) Deltamarine	
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 modelling [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. Noise levels from the model propeller are extrapolated to full scale using a variety of scaling rules. [78], [79]	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 model scale comparison and extrapolation can be found in [76].	Approximately 20 commercial model testing facilities have cavitation tunnels. Large scale tunnels are preferable to reduce scaling uncertainties. [74]	**9**
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**

APPENDIX 2

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