BEST AVAILABLE TECHNOLOGY (BAT) AND BEST ENVIRONMENTAL PRACTICE (BEP) FOR MITIGATING THREE NOISE SOURCES: SHIPPING, SEISMIC AIRGUN SURVEYS, AND PILE DRIVING

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Best Available Technology (BAT) and Best Environmental Practice (BEP) for Mitigating Three Noise Sources: Shipping, Seismic Airgun Surveys, and Pile Driving

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Sleeping adult sperm whales surrounding calves as they doze at 5m depth, Commonwealth of Dominica under government-issued permit © Arun Madisetti

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Abstract

The application of Best Available Techniques/Technology (BAT) and Best Environmental Practice (BEP) is often referenced in Decisions and Resolutions of numerous international agreements and conventions.

For shipping noise, this generally includes minimizing cavitation by various techniques such as better maintenance, and optimizing the propeller design, which often improves efficiency as well.. Focusing quieting on the 10-15% of the noisiest container and cargo ships will go furthest in reducing overall shipping noise. Slow steaming, or reducing ship speed mainly to save fuel, from an average of 16 kts to 14 kts (12% speed reduction) as was done in the Mediterranean, probably reduced the overall broadband acoustic footprint by over 50%. Slow steaming has the advantage that no retrofitting is required, and greenhouse gas emissions are reduced.

For seismic airgun surveys, quieting technologies, such as Marine Vibroseis, that could replace airguns show the most promise, as much of the energy (the mid- or high-frequencies) emitted by airguns is wasted and unused. A controlled sound source, like Marine Vibroseis, tailor-made to the specific environmental conditions and without the damaging sharp rise time of airguns would also likely be more environmentally friendly towards marine life. Mitigation measures for airgun surveys should show proof of their efficacy and should include: avoiding sensitive areas and times, not proceeding in conditions of poor visibility such as at night (unless technologies and techniques that are as effective as mitigation in good visibility are developed), establishing statistically meaningful baseline studies of biological abundance and distribution, and providing a thorough quantitative analysis of synergistic and cumulative impacts from other noise and non-noise stressors. If the latter cannot be achieved, adequate precaution must be built into the decision-making, and these gaps in analysis must be made explicit. Quieting technologies would almost certainly require much fewer additional mitigation measures.

Many new quieting technologies and alternative low-noise foundation concepts have been developed for pile driving, mainly due to the German government setting an action-forcing standard and noise limit. The great variety of quieting technologies and noise abatement systems for pile driving is in stark contrast to the lack of innovation that is occurring for quieter alternatives to the seismic airgun, where, for instance, Marine Vibroseis has been in development since 2008 and yet little progress is evident. For both seismic airgun surveys and pile driving, Best Available Technologies will likely be more effective than Best Environmental Practice, unless BEP is siting activities away from sensitive marine life.

At least 150 marine species have shown impacts from ocean noise pollution, but it has been difficult to specify the exact scenarios where ecosystem and population consequences from underwater noise will occur. Therefore, managing this threat requires a precautionary approach. Application of quieting technologies that reduce sound at source will likely be the most effective way to reduce the environmental impacts of underwater noise, and quieting methods that have additional benefits, such as reducing greenhouse gas emissions or encouraging technological innovation should be especially encouraged.

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Preamble

To prevent and reduce marine pollution, the application of Best Available Techniques/Technologies (BAT) and Best Environmental Practice (BEP) is a necessity. This is also recognized and promoted within Decisions and Resolutions adopted by the Parties under several international agreements and conventions, e.g., under the Convention on the Conservation of Migratory Species of Wild Animals (CMS) and the Convention on Biological Diversity (CBD). Regional Agreements, such as the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention) and the Convention on the Protection of the Marine Environment of the Baltic Sea Area (Helsinki Convention), as well as species-focused regional agreements, including the Agreement on the Conservation of Cetaceans in the Black Sea, Mediterranean Sea and Contiguous Atlantic Area (ACCOBAMS) and the Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas (ASCOBANS), also call for the use of BAT and BEP.

For the purposes of this report, the term "best" is used as in Best Available Technology and Best Environmental Practice, to mean best and practical for what is possible and realistic now, with the choices we have at present. However, these recommendations are still just steps toward true "best" and require ongoing innovation and adjustment to achieve more substantive reductions of negative impacts from noise on marine species and their habitat. "Best" here does not mean the ideal for maintaining or restoring ocean health.

CMS and Marine Noise Pollution

Given the importance of noise-related impacts to many species listed on the CMS Appendices, as well as their prey species, CMS Parties in Resolution 12.14 Adverse Impacts of Anthropogenic Noise on Cetaceans and Other Migratory Species outline the actions necessary to mitigate impacts of underwater noise on migratory species and their prey. Key recommendations include to:

- control the impact of marine noise pollution in habitats of vulnerable species and in areas where marine species that are vulnerable to the impact of anthropogenic marine noise may be concentrated;
- undertake relevant environmental assessments on the introduction of activities that may lead to noise-associated risks to CMS-listed marine species and their prey;
- prevent adverse effects on CMS-listed marine species and their prey by restricting the emission of underwater noise;
- adopt mitigation measures on the use of high intensity active naval sonars until a transparent assessment of their environmental impact on marine mammals, fish and other marine life has been completed;
- ensure that Environmental Impact Assessments take full account of the effects of activities on CMS-listed marine species and their prey and consider a more holistic ecological approach at a strategic planning stage;
- apply 'Best Available Techniques' and 'Best Environmental Practice' including, where appropriate, clean technology, in an effort to reduce or mitigate marine noise pollution;
- use, as appropriate, noise reduction techniques for offshore activities such as: air-filled coffer dams, bubble curtains or hydro-sound dampers, or different foundation types (such as floating platforms, gravity foundations or pile drilling instead of pile driving);
- integrate the issue of anthropogenic noise into the management plans of marine protected areas;
- facilitate regular collaborative and coordinated temporal and geographic monitoring and assessment of local ambient noise (both of anthropogenic and biological origin);
- further the understanding of the potential for sources of noise to interfere with long-range movements and migration;
- compile a reference signature database, to be made publicly available, to assist in identifying the source of potentially damaging noise sources;
- characterize sources of anthropogenic noise and their propagation to enable an assessment of the potential acoustic risk for individual species in consideration of their sensitivities to noise;
- conduct studies on the extent and potential impact on the marine environment of high- intensity active naval sonars and seismic surveys in the marine environment; and the extent of noise inputs into the marine environment from shipping and to provide an assessment, on the basis of information to be provided by the Parties, of the impact of current practices;
- conduct studies reviewing the potential benefits of 'quiet areas', where the emission of underwater noise can be controlled and minimized for the protection of cetaceans and other biota;
- establish national noise registries to collect and display data on noise-generating activities in the marine area;
- develop provisions for the effective management of anthropogenic marine noise in CMS daughter agreements and other relevant bodies and Conventions; and
- strive, wherever possible, to ensure that activities falling within the scope of this Resolution avoid harm to CMS-listed marine species and their prey.

The CMS Family Guidelines on Environmental Impact Assessment for Marine Noise Generating Activities (Annex 1 to Resolution 12.14) are designed to help Parties to make effective use of Environmental Impact Assessments (EIA), taking noise-related considerations into account already at the planning stages of activities.

More information on marine noise and the interests and activities of CMS can be found on this webpage: https://www.cms.int/en/topics/marine-noise.

This issue of the CMS Technical Series, mandated by the 13th Conference of the Parties to CMS and an output of the Joint Noise Working Group of CMS and its cetacean-related daughter Agreements ACCOBAMS and ASCOBANS, aims to assist Parties and industry by providing an up-to-date overview of the currently available Best Available Technology (BAT) and Best Environmental Practice (BEP) for mitigating noise from shipping, seismic airgun surveys, and pile driving.

1.1 BAT for Shipping Noise

Noise levels

Peak spectral levels for individual commercial ships are in the frequency band of 10 to 50 Hz and are around 195 dB re μPa2/Hz at 1 m for fast-moving (>20 knots) supertankers (Hildebrand 2009). A cargo vessel (173 m length, 16 knots) had a source level of 192 dB dB re 1 μPa at 1 m over a 40–100 Hz bandwidth (Hildebrand 2009). This does not mean that shipping noise is restricted to these low frequencies, however. Especially close by and in shallow water, shipping noise can extend into the high kilohertz (kHz) range. Hermannsen et al. (2014) found that vessel noise from various different ship types considerably raised noise levels across the entire recording band from 25 Hz to 160 kHz at ranges between 60 and 1000 m. The authors estimated that these noise levels caused a hearing range reduction in animals such as the harbour porpoise of more than 20 dB (at 1 and 10 kHz) from ships passing at distances of 1190 m, and more than a 30 dB reduction (at 125 kHz) from ships at 490 m distance or less (Hermannsen et al. 2014). This hearing range reduction (20-30 dB) represents a 100- to 1000-fold reduction in intensity.

Impacts

Shipping noise is associated with increased stress levels in endangered North Atlantic right whales (Rolland et al. 2012). Pirotta et al. (2012) found that broadband ship noise caused a significant change, over a distance of at least 5.2 km, in beaked whale movement while they were foraging, which could reduce their food intake. Routine vessel passages reduced communication space by up to 61.5% for bigeye fish and 87.4% for Bryde's whales, and by up to 99% for both species during the closest point of approach of a large commercial vessel (Putland et al. 2018). Larval Atlantic cod exposed to shipping noise in the laboratory were in worse condition and easier to catch in a predator-avoidance experiment (Nedelec et al. 2015). Indicators of stress increased with ship noise playbacks in European perch, common carp, and gudgeon (Wysocki et al. 2006), European sea bass and gilthead sea bream (Buscaino et al. 2010; Celi et al. 2016), juvenile European eels (Simpson et al. 2015), as well as shore crabs (Wale et al. 2013). Shipping noise caused bluefin tuna schools to become uncoordinated, which could affect their homing accuracy during migration (Sarà et al. 2007).

Excessive underwater noise from ships is mainly caused by poor propeller design or one not correctly matched to

Picture 1. Around 90% of global traded goods are transported by ships, with further steep increases in volume projected, underlining the urgency of consistent application of BAT and BEP to make this development as environmentally friendly as possible. © Canva.com

the vessel and its usual operating conditions; poor ship hull design especially of the aft end of the ship, causing an uneven water flow into the propeller (poor wake field); or a fouled (dirty) or damaged propeller. A particularly noisy propeller means the ship is probably operating inefficiently. Solutions to existing ships include installing new, more efficient propellers, good maintenance of propellers (cleaning and repairing damaged ones), using devices to improve the wake flow into the propeller, and maintaining the hull well.

Propeller cavitation

Propeller cavitation is a major source of shipping noise. It is caused by the formation and collapse of air bubbles on the surface of a rotating propeller when the pressure falls below the vapor pressure of water, causing a hissing noise. It is broadband, across a wide range of frequencies, but with narrow-band or tonal peaks of noise occurring together with the rotation rate (rpm) multiplied by the number of blades of the propeller, and the harmonics thereof. The lowest speed where cavitation starts to occur is known as the cavitation inception speed (CIS). For many ships, the CIS is around 10 kts or even lower (Leaper and Renilson 2012). Some cavitation occurs even with efficient propellers, but excessive cavitation from the noisiest ships is a sign they may be operating inefficiently, with poor wake flow into the propeller and/or poor propeller design (Leaper et al. 2014). If noise from one source of noise is 10 dB above other sources of noise, then those other sources are mostly irrelevant (McCauley et al. 1996). For the noisiest merchant ships, the propeller cavitation noise is likely to dominate other noise sources from that ship (IMO 2013). Cavitating propeller noise dominates other propeller noise, other than singing (high-pitched notes), and all other hydro-acoustic noise from a ship (Ligtelijn 2007). Propeller singing is easy to fix by changing the shape of the trailing edge (Leaper and Renilson 2012).

Overlap between increased energy efficiency and noise reduction

As Leaper and Renilson (2012) explain it, a greater blade area can produce the same thrust but with a smaller difference in pressure between the face (pressure side) and the back (suction side) of the blade. Since the difference in pressure causes cavitation, cavitation will be reduced with increased blade area. However, this greater blade area also increases the necessary torque required to turn the propeller. For merchant ships, there is an optimum design in terms of efficiency that is a trade-off between cavitation and blade area. In most cases, an optimally efficient propeller involves a certain amount of cavitation to minimize blade area. It should be the goal, however, to reduce excessive cavitation which can reduce the thrust and also cause erosion on the propeller and even on the rudder, in some cases (Leaper and Renilson 2012). It has been very roughly estimated that a 5-10 dB reduction in noise can be achieved before there is a loss in efficiency, though. This will, however, very much depend on the specific circumstances. This amount of quieting would reduce the acoustic footprint of ships greatly and substantially improve the quality of the environment. The amount of quieting necessary is relatively modest, not on the order of that required of stealthy naval vessels.

The other major factor involved in reducing propeller cavitation is improving the wake flow around the hull ahead of the propeller. Improved wake flow will both reduce noise and improve efficiency. Ideally, the wake should be as uniform as possible, so that the propeller, as it rotates through its full circle, does not experience much of a difference in flow. A non-uniform wake can reduce propulsive efficiency and cause the cavitation to fluctuate through the rotation cycle, producing tonal noise and harmonics thereof. Hull shape can also influence the wake going into the propeller (Chris Waddington, pers. comm.). The bulbous stern is designed to provide clean flow into the propeller, and thereby reduce cavitation and noise (Chris Waddington, pers. comm.). Thus, designs for new build ships should be assessed using appropriate modelling techniques to optimize the propeller and hull configuration with respect to underwater radiated noise. Similar modelling may also help with retrofitting existing ships with wake flow devices or optimised propellers.

Propellers should be clean, free of fouling, polished, and well-maintained, with no nicks or imperfections, especially on the leading edge (Leaper and Renilson 2012). Such damage can cause more cavitation, reduce efficiency by around 2%, and cause noise (Leaper and Renilson 2012). Propellers should be assessed and repaired at each dry-docking of a vessel with respect to any damage that might cause an increase in noise. Well-built and well-designed propellers can help with efficiency and noise, and care should be taken to design the propeller and hull as a unit, so that the wake field is taken into account. Designs of propellers and hulls should suit the actual operating conditions, not the ideal. This would also improve propulsive efficiency and reduce noise (Leaper and Renilson 2012).

Propellers can also generate vortices from their hub which reduce efficiency and are prone to cavitate (Leaper and Renilson 2012). They also tend to cause higher frequency noise. Efficiency gains and noise reduction can be achieved by well-designed hub caps as well as devices that can be affixed to the hub such as Boss Cap Fins and Propeller Cap Turbines (Leaper and Renilson 2012).

Optimising the wake flow is always most effective if done at the design stage, but for existing vessels known to have less than optimal wake flow there may be scope for minor modifications. Wake inflow devices can improve the wake going into the propeller, reducing cavitation and likely increasing efficiency while reducing noise. Devices that can be fitted to the hull for this purpose include the Schneekluth duct, Mewis duct, and Grothues spoilers (Leaper and Renilson 2012).

In 2009, the IMO (International Maritime Organization) recommended that member states should identify the vessels in their merchant fleets that would benefit most from efficiency-improving technologies as these would also likely make their ships quieter (IMO 2009a). Most importantly, as fuel efficiency and greenhouse gas emissions are tackled, it would be a missed opportunity to not address noise at the same time, as there is certainly some overlap. Small changes in propulsive efficiency can dramatically lower noise output (Leaper and Renilson 2012).

Hull vibration, engine and machinery noise

Vibration isolation, noise insulation, and damping are the main treatments to reduce noise and vibration to the hull from onboard machinery. Although generally lower level in terms of broadband sound energy than noise from the propeller, onboard machinery can generate tonal sounds.

Onboard real-time noise monitoring

A real-time noise or cavitation monitoring system using onboard sensors for both engine and propeller noise would also be helpful, so that ship operators can get immediate feedback about which operating conditions (e.g., trim) are producing the most noise and cavitation. For propeller noise, sensors may be mounted near the propeller for real-time noise monitoring onboard. This can tell the operator which conditions alter the cavitation inception speed or change the noise output. Studies underway as part of the Saturn project will provide detailed comparisons of measurements from on-board sensors and measurements of underwater radiated noise levels.

Technological quieting measures

A report was prepared for Transport Canada by Vard Marine Inc. (Kendrick and Terweij 2019) to systematically describe all the technological quieting measures for ship underwater radiated noise. This did not include operational or maintenance measures. A table was included in the report which is copied in the Appendix, with permission. The matrix was developed by Vard Marine on behalf of Transport Canada and is based on an extensive literature search and the input of industry experts in a series of workshops (Kendrick and Terweij 2019).

Picture 2. The critically-endangered European Eel (*Anguilla anguilla*) is amongst the many species shown to be negatively affected by marine noise © Bernard DUPONT from FRANCE (*European Eel (Anguilla anguilla)*) [CC BY-SA 2.0 (http://creativecommons.org/licenses/by-sa/2.0)], via Wikimedia Commons

Noise consideration in ship design

If tank testing facilities and model basins measured noise routinely and incorporated noise reduction as a factor in good ship design, ships would be designed to be quieter from the onset. With the emphasis on ever-increasing fuel efficiency, there are opportunities to improve the design process of ships such that the design starts with the propulsion system rather than designing a propulsion system to suit a given hull design. This has the potential to improve efficiency and reduce underwater noise.

1.2 BEP for Shipping Noise

Slow steaming to reduce noise

Slow steaming is the practice of operating transoceanic cargo ships, especially container ships, at substantially slower speeds than their maximum, mainly to save fuel. Slow steaming has the advantage that no retrofitting is required so can be implemented immediately. For ships with a fixed pitch propeller, which are the majority (controllable pitch propellers were only used in 10% of tankers, 1% of bulk carriers, and 9% of container ships in 2000-2004 (Carlton 2007)), reducing the speed reduces the overall noise, though levels may not necessarily decrease across all frequency bands (Leaper and Renilson 2012). Leaper et al. (2014) noted that slow steaming practices since 2007 reduced average speeds from 15.6 kts (sd = 4.2) in 2007 to 13.8 kts (sd = 3.0) in 2013 for ships using the major shipping routes in the eastern Mediterranean. This 11.5% reduction in average speed probably reduced the overall broadband acoustic footprint from these ships by over 50% (Leaper et al. 2014). For ships around the Haro Strait (between Seattle and Vancouver), 3 dB of overall noise reduction (i.e., a 50% reduction in sound energy) could be met by enforcing a speed limit of 11.8 knots (Veirs et al. 2018). The average ship speed across all classes was 14 kts; the average for container ships alone was 19 kts. This speed limit would affect 83% of the ships studied (Veirs et al. 2018). Dunn et al. (2021) found that slower ship speeds due to COVID-19 resulted in lower ocean noise pollution. Vessel speed was highly correlated to Sound Pressure Level (SPL) of the noise and was the only ship-based variable that predicted SPLs. MacGillivray et al. (2019) discovered from a two-month long trial where ships slowed down to 11 knots, that lowering speed was an effective method for reducing mean broadband source levels of noise for five categories of piloted commercial vessels: containerships (11.5 dB), cruise vessels (10.5 dB), vehicle carriers (9.3 dB), tankers (6.1 dB), and bulkers (5.9 dB).

There is a concern that slower ships produce overall more noise over time (larger Sound Exposure Levels - SELs) because they remain in an area for longer. This is not true, however, since Underwater Radiated Noise (URN) is correlated with the sixth power of speed (Leaper 2019), which is a very steep curve, and time is just linear, so slower ships will produce lower SELs as well as lower Sound Pressure Levels (SPLs).

Slow steaming to reduce noise and co-benefits with greenhouse gas emission reduction

Slow steaming across shipping fleets has also been shown to be an effective short-term measure to reduce greenhouse gas emissions. In April 2018, the IMO adopted the goal to reduce the total annual greenhouse gas emissions by at least 50% by 2050 compared to 2008. To this end, the IMO has introduced various CO_2 reduction measures that have the potential to drive a reduction in vessel speed and thus, noise reduction. The Energy Efficiency eXisting ship Index (EEXI) is a technical design-related measure for existing ships above 400 gross tons, to be applied after 1 January 2023. Many vessels may achieve compliance by adopting overridable power limitations, i.e., they will slow down (Chris Waddington, pers. comm.). The Energy Efficiency Design Index (EEDI) provides a new building standard, assuring that ship designs achieve a certain level of efficiency and decrease carbon emissions. It was introduced in 2013 for new vessels of 400 gross tons and above. Vessels need to meet the reference level for their ship type, which is tightened every 5 years. Ship owners can select the efficiency measures they regard as most appropriate, which may include speed reduction (Chris Waddington, pers. comm.). Unlike EEDI and EEXI which are design indices, the Carbon Intensity Indicator (CII) is an operational measure for which there is an annual reporting requirement. It is a non-prescriptive measure of how efficiently a ship transports goods or passengers and is given in grams of CO_2 emitted per cargo-carrying capacity and nautical mile. It will apply to new and existing ships above 5,000 gross tons beginning 1 January 2023. The extent to which these measures will reduce overall vessel speeds and consequent underwater noise has yet to be fully assessed. To some degree, this will depend on ongoing discussions within IMO on ways to reduce GHG emissions. Rutherford et al. (2020) suggest that most ships are being operated at engine loads that would be unaffected by the technical efficiency standard the EEXI sets, and thus the entry in to force of EEXI requirements may not result in substantial speed reductions. However, speed reduction can be a very effective way of reducing emissions, and it is possible that some ship owners may adopt further speed reductions beyond those they may have adopted for EEXI compliance (Chris Waddington, pers. comm.). A further proposal has been made for an overridable power option to be available for EEDI compliance (new ships). This is the same overridable power option that can be used for EEXI compliance (existing ships). If adopted, this may lead to further speed reductions of new vessels (Chris Waddington, pers. comm.).

Leaper (2019) reviewed modelling work on greenhouse gas emissions, and how that related to underwater noise, ship-whale collision risk, and ship speed. He took into account research which considered that slow steaming would increase the number of vessels needed to transport the same volume of goods, the cost of operating those extra vessels, and the increase in ship construction that might be necessary. Faber et al. (2017) examined speed reductions of 10, 20 and 30% compared to ‘business as usual’. They found that in 2017, 3.5% of container vessels were idle or laid up and estimated

Picture 3. Cetaceans (whales, dolphins and porpoises) are amongst the species most vulnerable to marine noise. Northern Right Whale © Canva.com

that bringing these vessels back into service would allow the container fleet to reduce speeds by 8% (Faber et al. 2017). Speed reductions of greater than 10% would probably require an increase in fleet capacity to meet current demand (Leaper 2019). According to an economic model developed by Lee et al. (2015), the savings in total fuel consumption from slowing down was usually higher than the cost of operating the extra vessels necessary to transport equivalent goods. In addition, slow steaming also had business advantages beyond saving fuel in that it increased delivery time reliability (Lee et al. 2015). Leaper (2019) examined various speed reduction scenarios which would help achieve the greenhouse gas reduction targets, while at the same time offering additional environmental benefits of reducing noise and the risk of ship strikes on whales. Leaper (2019) concluded that modest, 10%, reductions in speeds across the global fleet could reduce the total sound energy produced by shipping by around 40%.

The reduced risk of ships striking whales was harder to estimate, with greater attendant uncertainty, but could be around 50% for a 10% reduction in speed across the fleet as a whole (Leaper 2019). When slow steaming is used, the propellers and hull should be redesigned for this operational difference, especially controllable pitch propellers (CPPs) (Leaper and Renilson 2012). The proportion of the long-distance commercial fleet with CPPs is very low, but consideration of noise from such propellers may be important in localized situations, for example where CPPs are fitted to ferries.

While slower speeds with the same fixed pitch propeller will almost certainly substantially reduce noise levels because cavitation will be reduced, it is more complicated if the propeller is optimised for the slower speeds in terms of fuel efficiency. This is because optimising for fuel efficiency may involve reduced blade area and accepting a greater amount of cavitation. There is a need to consider underwater noise as well as fuel efficiency when making such modifications such that noise is not inadvertently increased by optimising for fuel efficiency.

Vessel load condition

Propellers are usually designed for vessels carrying a full load, despite ships not spending all their time in this state (Leaper and Renilson 2012). In ballast, the ship is never loaded close to its full load condition, which means the propeller is closer to the surface. The propeller tip may even be above the waterline. In ballast, the degree of cavitation on a propeller can be increased because of the reduction in water pressure on the blades, despite reduced propeller loading (Paik et al. 2013). On top of that effect, a ship in ballast is usually trimmed by the stern which worsens the wake field to the propeller, causing yet more cavitation (Leaper and Renilson 2012).

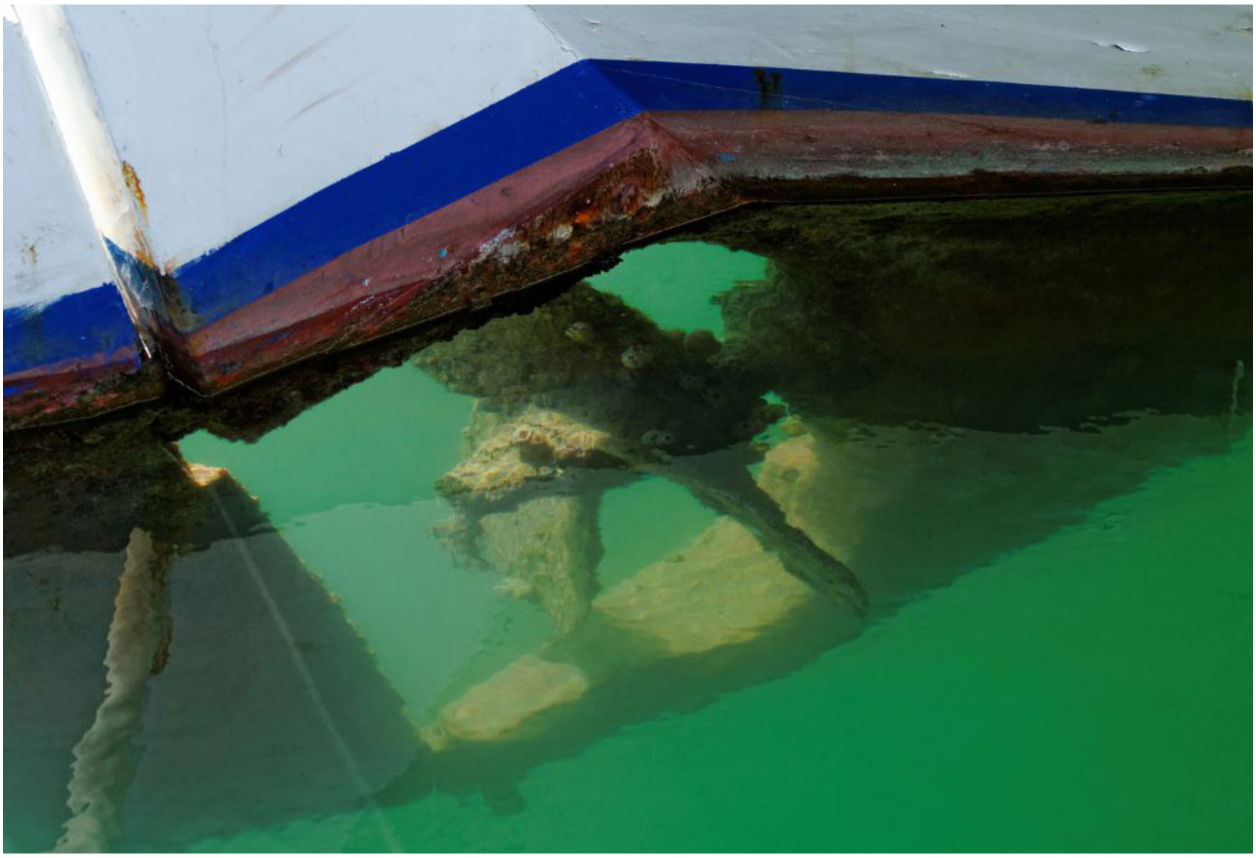
Altogether, this means a tanker or bulk carrier in ballast will often be noisier than one in full load (Leaper and Renilson 2012). Some possibilities to address this include installing air injection to a propeller in ballast conditions or Ship Trim Optimization software. The development of on-board sensors that can provide a reliable indication of underwater noise may also assist in adjusting vessel trim.

Cold ironing

Cold ironing is the practice of using a shoreside electrical power connection when a ship is at berth in port while its main and auxiliary engines are turned off. It is also called shore-to-ship power (SSP) or alternative maritime power (AMP). There is obviously less underwater noise with cold ironing, as well as fewer emissions. There may be an added advantage of cold ironing in that it may reduce biofouling on ship hulls. Several studies have shown faster settlement of mussel larvae or other biofouling organisms with ship or generator noise (Jolivet et al. 2016, McDonald et al. 2014, Stanley et al. 2014, Wilkens et al. 2012). Only one study showed a low-frequency sound inhibiting only very young barnacle larvae from settling (Branscomb and Rittschof 1984). Reducing biofouling can save money (the U.S. Navy spends US$1 billion every year and US$56 million per single Navy vessel class on biofouling—McDonald et al. 2014), reduce noise (biofouling increases turbulence), increase efficiency, and even avoid the spread of invasive species on hulls. Vessel hull biofouling can be responsible for at least 75% of the invasive species brought in by ships (McDonald et al. 2014). A clean vessel entering a port infected with invasive species and running a generator could attract pest species from about a 500 m radius (McDonald et al. 2014).

Acoustic anti-biofouling systems

The use of acoustic anti-fouling has increased sharply in the last few years and is likely very damaging to beaked whales and other cetaceans. Though this technology has been available since about 2007-2012, only recently (since around 2022) has it become ubiquitous. Legg et al. (2015) reviewed various acoustic anti-fouling systems, concluding that around 20 kHz is optimal to reduce the settling of most invertebrates. Most systems operate between 17-30 kHz. Martin et al. (2022) found that these devices elevated received levels by 40 dB in the 20-30 kHz range. Their median energy source level (0.1 seconds) was 183 dB re 1 μPa^{2}s. Disturbance to high-frequency sensitive cetaceans was estimated to be around 3 km, with potential to cause temporary or permanent hearing damage quickly. There was an almost complete listening range reduction for high-frequency echolocation up to a distance of 5 km, lasting 25 minutes for a 14 kt vessel, when the device



Picture 4. Biofouling increases fuel consumption and underwater noise. © Canva.com

was mounted on the hull (Martin et al. 2022). Trickey et al. (2022) found hull-mounted ultrasonic anti-fouling devices on tourist vessels caused clear avoidance by Cuvier's beaked whales. These devices started at 19 kHz, ranging up to 42 kHz or more, with a transmission range of over 2 km.

Maintenance

Keeping the hull and propeller clean and repaired can yield cost savings, efficiency gains, and noise reductions. Other onboard machinery and engines will almost certainly be quieter and more efficient when well-maintained. Proactive in-water ship hull grooming, where the hull is cleaned before it is badly fouled, can also help with both reducing noise and increasing efficiency (Swain et al. 2022). Based on an analysis of the frequency of fouled vessels and the additional drag associated with fouling (Munk et al. 2009) around 50% of vessels may need an extra 30% of power to maintain cruising speed. Based on observed relationships between URN (Underwater Radiated Noise) levels and engine power (Leaper 2019), an increase in required power of 30% would likely result in an increase in URN of 2.3dB. Munk et al. (2009) found around 17% of vessels had an increased drag of greater 50% which would likely increase URN levels by more than 3.5dB. These increases in URN levels would greatly increase the number of animals unnecessarily affected. The rate of fouling varies considerably between areas and depending on the operational pattern of the vessel. The level of fouling should be regularly assessed so that it can be addressed as soon as it is likely to have a measurable effect on drag.

Shipping lane re-routing around important habitat

Re-routing shipping lanes around areas rich in marine life can reduce ship-whale collision risk as well as reduce exposing sensitive areas to noise. Routing measures already exist within some PSSAs (Particularly Sensitive Sea Areas) designated by the IMO, and the IMO has recognised changes in routing as the most effective way to reduce ship strike risks. Sometimes these routing changes can be quite small to nevertheless reduce ship strike risk. Since Resolution A.982(24) already references noise as one of shipping's impacts on the environment, noise could be applied as a criterion in the designation of PSSAs. Such sensitive areas may need to be larger to address noise compared to other impacts, because noise can travel long distances. In particular, critically endangered riverine cetacean species, due to their confined environment, are especially vulnerable to the low frequencies of loud underwater noise from large vessels (>100 metric tonnes), and the higher frequencies of smaller high-speed vessels. Impacts could include temporary or permanent hearing damage or acoustic masking of important signals for communication, feeding, or orientation; or boat collisions and displacement from important habitat, which is limited in a riverine situation (Kreb and Rahadi 2004, Prideaux 2017). Therefore, the implementation of defined shipping lanes for large vessels, i.e., staying in the center of the river, avoiding narrow tributaries (<100 m width), and limiting large vessels passage only to river parts which are more than twice the depth of the draught of the ship, is considered a best practice. High-speed vessels should reduce speed to wake speed in important feeding areas, as indicated by board signs.

Avoiding times/areas of high sound propagation

Sound propagates or travels further in certain conditions. Noise produced at the surface can enter the deep sound channel, in which sound travels long distances very efficiently, where the sound channel intersects with features such as the continental slope (Leaper and Renilson 2012). The sound channel tends to be close to the surface in high latitudes. As a general rule, in colder months, sound is also transmitted further than in warmer ones, especially in deep water. Thus, to reduce the spread of shipping noise, ships on long oceanic passages may be able to adopt minor routing changes, possibly reducing the amount of time travelling parallel to the continental slope or shelf by staying further offshore and, if they must cross the continental shelf, to do so at right angles. While more difficult, reducing time at colder, higher latitude waters, and operating in the warmer months, where possible, could also help to lessen noise propagation.

Port incentives

In 2017, the Vancouver Fraser Port Authority and the Port of Prince Rupert both introduced financial incentives to quieter ships in the form of reductions in docking fees and harbor dues of up to almost 50%. Ships needed a quiet ship certification from an international ship classification society, such as American Bureau of Shipping (ABS), Bureau Veritas (BV), Det Norske Veritas Germanischer Lloyd (DNV), Lloyd's Register (LR), and Registro Italiano Navale (RINA). Best Practice for measuring and certifying noise from ships might be a combination of various methods such as computational predictions validated by onboard measurements over a range of speeds, with perhaps one or two at-sea measurements to verify these. Such incentives for quieter ships should be expanded to other ports worldwide to create a level playing field.

Certification programs

Green certification programs that incentivize quieter ships such as Green Marine can help reduce ocean noise pollution from shipping. Ships that reduce emissions and are otherwise more environmentally friendly can gain standing and ranking and are able to advertise their green credentials.

Underwater noise management plans

Underwater noise management plans can be developed for individual vessels or for all the vessels using a particular area. For example, Transport Canada has encouraged Canadian vessel operators to have plans to reduce their fleet's overall noise output. Noise Management Planning is the development of a plan to reduce URN and achieve URN goals. Such a plan should measure a noise baseline, set a goal or target, and define operational, organizational, and technological measures to reduce noise. These measures should repeatedly be evaluated to determine their effectiveness. Moreover, such noise management plans should become mandatory, as should the targets.

To this end, a 5-grade scale (A-E, similar to the Carbon Intensity Indicator) could be developed for URN, as this approach is familiar to the industry. Depending on the rating during an annual review, the ship could be required to install design upgrades or conduct significant operational improvements. Each ship could be evaluated for noise, and guidance given on how to make it quieter. The emphasis here would not be to meet a particular noise target, but rather to make each ship as quiet as possible within the scope of its operational requirements and size, as per the noise management plan for that vessel. Additionally, it would allow for ships to understand the extent of measures that they should consider, to reduce URN to less adverse levels. It would also hopefully direct attention to the noisiest ships first.

Focus on the noisiest vessels

Setting source level standards for each vessel type is challenging. Focusing on the noisiest vessels aims to achieve the most benefit with the least economic impact, as the noisiest vessels may well be operating inefficiently. There have been differences of 20-40 dB reported between the quietest and noisiest ships of a similar type (Carlton and Dabbs 2009), showing large differences in levels at certain frequencies. Leaper and Renilson (2012) estimated that the noisiest 10% of vessels (those that are 6.8 dB or more over the average) contribute to 48-88% of the total acoustic footprint (the sea area over which the ship noise increases the background noise over a certain level). Veirs et al. (2018) found that, of 1,582 ships measured in the Haro Strait between Seattle and Vancouver, half of the total power radiated by this modern fleet came from just 15% of the ships--those with source levels above 179 dB re 1 μPa at 1 m. More than two-thirds of these worst noise polluters were cargo and container ships (Veirs et al. 2018). About 43% of container ships were worst polluters, by far the highest proportion of any ship class of those studied (Veirs et al. 2018).

1.3 BAT for Seismic Airgun Survey Noise

Noise levels

An airgun array has a nominal source level of around 260 dB re 1 μPa at 1 m (SPL), with a bandwidth of 5-300 Hz (Hildebrand 2009). While the energy from airgun impulses is mostly concentrated in the lower frequencies, there is still substantial energy in the tens of kHz to even over one hundred kHz (Goold and Coates 2006).

Impacts

Fin whales were displaced from their habitat when a seismic survey started, and the displacement lasted well beyond the 10-day length of the seismic survey (Castellote et al. 2012). Bowhead whale calling was repressed within a 50–100 km radius of a seismic survey, which represents 8,000-30,000 sq km in area. Within 10–40 km of the seismic survey, or 300–5,000 sq km, bowhead calling was almost entirely absent (Blackwell et al. 2015). Pirotta et al. (2014) found that the probability of recording a prey capture attempt by harbour porpoise declined by 15% in the 25 km x 25 km area exposed to seismic survey noise compared to a control area and increased the further away the seismic vessel was. Seismic airgun noise killed zooplankton, especially immatures, with a 2-3-fold increase in dead zooplankton at ranges of up to 1.2 km from the airguns (McCauley et al. 2017). Day et al. (2017) identified a 5-fold increase in mortality in scallops subjected to four passes of an airgun. These scallops received the equivalent of a full-scale array passing at 114- to 275-m range. Maximum peak-to-peak values were 191-213 dB re 1 μPa, maximum SELs were 181-188 dB re 1 μPa2·s, and maximum cumulative SELs, SELcum, were 194-198 dB re 1 μPa2·s. These effects occurred 4 months after exposure to the airgun ceased. Fitzgibbon et al. (2017) discovered that southern rock lobsters showed a chronic reduction of immune competency and impairment of nutritional condition, also 120 days post-airgun exposure. Received levels were roughly similar to or higher than those above: maximum peak-to-peak 209-212 dB re 1 μPa; maximum SELs 186-190 dB re 1 μPa2·s, and maximum SELcum, 192-199 dB re 1 μPa2·s. Mean exposures were equivalent to passage of a large commercial air gun array (2,000–4,000 cu. in.) within < 500 m range. Moreover, lobsters showed significant damage to sensory organs, impairing important reflexes, even a year post-exposure to an airgun (Day et al. 2019). The exposure was equivalent to a full-scale commercial array passing within 100–500 m, with levels as above. Catch rates for haddock, cod, and rockfish dropped from 21-70% (Engås et al. 1996, Skalski et al. 1992) during or after seismic airgun surveys. In the Engås et al. (1996) study, seismic shooting using a 5,000 cu. in. array occurred over a 5.5 km x 18.5 km area, and impacts were assessed over a 74 km x 74 km area. Skalski et al. (1992) used a single airgun exposing fish at a distance of about 165 m to peak levels of 186 dB re 1 μPa. Declines in fish abundance were also documented (Paxton et al. 2017, Slotte et al. 2004). Slotte et al. (2004) used a 3,000 cu. in. array, and the seismic survey area comprised about 51 km x 25 km. Fish abundance was measured up to 30-50 km away from the seismic shooting area. Paxton et al. (2017) examined fish communities 7.9 km from a seismic survey track, where received levels were estimated to be between 181 dB (spherical spreading) and 220 dB (cylindrical spreading) re 1 μPa (peak).

Lowering source levels and reducing high-frequency content

Leaper et al. (2015) found that there are seldom cases where mitigation based on visual observation can achieve a greater risk reduction than would be achieved by a 3 dB reduction in source level throughout the survey. This is because Marine Mammal Observers (MMOs) cannot spot many marine mammals and turtles since they are cryptic, elusive, often underwater, and since survey activities often take place at night and in other limited-visibility conditions. The use of MMOs therefore only results in a limited risk reduction in all cases (Leaper et al. 2015). Consequently, probably the most effective mitigation for seismic airgun surveys is to: a) separate the surveys from areas rich in marine life and sensitive species (most likely by avoiding times when sensitive species are present); and b) to lower the source level (quiet the noise). Seismic operators should be required to develop a detailed plan describing how they will minimize sound levels, including calculations of the minimum required levels to meet the survey objectives, how these will change within the survey area and with different weather conditions, and how the survey equipment will be configured to ensure only the minimum sound level is generated. If a 3 dB reduction in source level makes a great difference to the quality of the seismic data, then more controllable sources (e.g., Marine Vibroseis™, MV, see below) rather than airguns are essential to adapt to different conditions. Otherwise, seismic operators must use the source level that applies to the most difficult conditions expected during the survey, which may be much higher than is needed most of the time. This is wasteful and adds more environmental risk than is necessary.

As mentioned, there is still considerable energy in the tens of kHz from airguns, extending even to over 100 kHz (Goold and Coates 2006), which explains why cetaceans (whales and dolphins) with middle or higher frequency sensitivities react to the noise (Goold and Fish 1998). Geophysicists and the oil and gas industry do not make use of, nor even record, any energy over about 200 Hz, however. This wasted energy therefore needlessly impacts marine life, especially animals with mid- or high-frequency hearing. The high-frequency output is a by-product of generating the low frequencies, flattening the output spectrum, and increasing the primary to bubble ratio (Jenkerson 2022), but can be suppressed. There is currently effort being expended by several companies to develop alternative marine seismic sources that are expected to have a reduced environmental impact while being at least as effective as airgun arrays. It is very difficult to get more information on technological alternatives to airguns, as much is proprietary and still under development. Advances in receivers have enabled smaller output sources, though.

Several industry players have developed alternative pneumatic marine seismic sources that aim to limit bandwidth, increasing low-frequency content (Brittan et al. 2020), while reducing the higher frequency output. Pneumatic sources have been physically modified to reduce the high-frequency content by controlling the release of air in different ways, but generally by slowing the release of the air (Coste et al. 2014, Supawala et al. 2017, Tellier et al. 2021). This can also slow the rise time (fast, sharp rise times are injurious to living tissue—see below), and lower the SEL. In some cases, physical modifications to the source require changes to the way in which sources are operated, by using larger volumes, but at much lower pressures than would be used for the activation of traditional pneumatic sources (Tellier et al. 2021). Arrays of pneumatic sources are generally 'tuned', which normally means separating individual source elements such that the air bubbles created by each do not interact. However, placing elements close to one another in a 'cluster' can also result in coalescence, helping to produce a larger low-frequency peak output (Hopperstad et al. 2016). A hypercluster of standard airguns such as the Shearwater-Harmony™ also reduces the peak amplitude by tilting the output spectrum to lower frequencies (Hopperstad et. al 2012). (Jenkerson 2022). The ION-Gemini™ is an impulsive, high pressure-high volume cluster with reduced peak amplitude. There is no operational impact, but there is some cost in switching to the larger chamber design. It can be used as a stand-alone source or across the full seismic band. A separate chamber size is used for full band seismic imaging (Jenkerson 2022). These various methods can result in significant reductions in the signal strength at high frequencies (Brittan et al. 2020, Li and Bailey 2017, Tellier et al. 2021).

Teledyne Marine's eSource™ airgun, developed by Bolt Technology Corporation and WesternGeco, and Sercel's Bluepulse™ release air more gradually than the conventional airgun so that they attenuate or reduce the higher frequencies while optimizing frequencies in the seismic band of interest, to minimize the effects on marine mammals. The airgun head and port shape are modified, slowing shuttle velocity, and reducing acceleration distance. Both Teledyne and Sercel have kits to update standard airguns. Though this adds expense, they are still relatively low-cost mitigations as there is no significant increase in operational cost (Coste et al. 2014, Tellier et al. 2021). The eSource™ contains three sources in one tunable package, and two models are available. The advantage with this alternative is that it does not require any retrofitting of the seismic vessels, unlike MV, and can be used as a conventional airgun would be. The disadvantage is that the approach may be too piecemeal and not comprehensive enough, as other potentially damaging characteristics of airgun pulses remain. While the rise time is slowed and the SEL is lower, The eSource™ and Bluepulse™ still have a higher source level and a sharper rise time than MV, and are not controlled sources.

A consortium led by BP has developed the Wolfspar™ unit, a vibratory source focused more on very low frequencies. Large volume displacements are required to generate the low frequencies. Two field trials have been conducted in the Gulf of Mexico to date. Wolfspar™ from BP uses very low frequencies of around 1-2 Hz together with ocean bottom nodes. It is used to better image an oil or gas reservoir, particularly one below salt layers. Unfortunately, for full-band seismic imaging, a separate array must also be used in conjunction with Wolfspar™ (Jenkerson 2022).

In addition to limiting the bandwidth of sources, the way in which seismic sources are configured and activated has evolved in recent years. Most airgun arrays are designed to direct low-frequency energy downwards, though they often can produce sidelobes that project higher frequencies at more horizontal angles. Arrays can be designed to minimize more horizontal propagation, which would reduce environmental impacts. Traditionally, seismic sources are made up of dual arrays, activated alternately in what is termed 'flip-flop' mode, with an acoustic signal every ~10-12 seconds. Increasingly, there is a shift toward using multiple sources, with triple and quintuple sources common, as well as the coded activation of multiple individual source elements in a randomised activation pattern. Termed 'blended' or 'simultaneous' acquisition, such methods provide greater spatial resolution in the resultant image of the subsurface and can increase efficiency through facilitating larger receiver spreads to be deployed, resulting in less line kilometres being sailed per square kilometre of data acquired. The use of multiple smaller sources means reduced peak sound pressure levels and sound exposure levels, but with reduced time between each acoustic signal (Hager 2019, Hegna et al. 2019). While anything to reduce the SPL and bandwidth is helpful, the effectiveness of these modifications needs to be evaluated in terms of the reduction in SPL and also possible extended pulse times.

Picture 5. Increased noise levels from shipping and seismic airgun surveys have hindered fin whale (*Balaenoptera physalus*) communication, potentially affecting reproduction. © Canva.com

Desynchronizing or staggering airgun activation can reduce high-frequency output without affecting the low frequencies, and reduce peak pressure and SEL at minimal operational and capital cost. A small millisecond scatter in activation times can act like a high cut filter, reducing frequencies above a frequency defined by the distribution in firing times. A large scatter in firing times (sec) can produce a continuous wavefield, sounding like white noise, with a decrease of 20 dB in peak amplitude but an increase in duty cycle. Examples of large scatter in activation times (seconds) are E-seismic™ and popcorn™ (Jenkerson 2022).

Using mufflers, such as a bubble curtain, to lower the high frequencies is complex operationally, high cost, and not very viable, though a small bubble curtain in a ring around the airgun ports has shown some efficacy (Wehner and Landrø 2020).

The SERCEL TPS (Tune Pulse Source) is an impulsive pneumatic source that uses larger volume, air-filled chambers and lower pressures. It has zero acceleration distance, smooth ports, and a modified shuttle design releasing energy over a longer period (Tellier et al. 2021). The spectral output is mostly at frequencies under 10 Hz. It eliminates or reduces cavitation, and it has a slower rise time compared to conventional airguns. It was mainly developed for geophysical purposes where very low frequencies are needed, though there is also an environmental benefit to reducing the higher frequencies (Ronen 2022). TPS is 13x quieter in maximum SPL than a conventional airgun array. The frequency at which the source signal gets lost in the background noise is at 140 Hz for TPS vs. 1 kHz for airguns, at 15 km distance; 2 kHz for TPS vs. 25 kHz for airguns at a distance of 3 km. TPS can work as a stand-alone survey even without being supplemented by higher frequency sources, unlike very low-frequency sources such as Wolfspar™, and has been used commercially (Ronen 2022).

Ultimately, the choice of source type and acquisition method is dependent on multiple factors, including the geophysical objectives and how they can best be met given the geological setting of the survey area. It is also the case that many of the technologies are proprietary to individual companies, and therefore not commercially available to all survey contractors to use. This will present a problem for regulators. If an operator is using a source that is more environmentally impactful than another company's, they cannot claim to be using the minimum source level, as some laws require.

Marine Vibroseis™ (MV)

Another principle is to replace the short, high amplitude, wide frequency-bandwidth signal produced by an airgun array with a much longer, lower-amplitude signal, with the same acoustic energy in the frequency band required for the seismic survey (below 200 Hz and sometimes below 120 Hz). Frequencies under 100 Hz are required for effective imaging. The useful signal would have the same energy, just spread over a longer duration, allowing for a lower source level and less wasted energy at frequencies that are not used. The effectiveness of a signal for seismic surveying is determined solely by the signal's energy and bandwidth, so a longer, quieter signal should be just as effective as a shorter, louder one provided they have the same energy and cover the necessary frequencies. The quieter signal should reduce the risk of damage to an animal's hearing at short range.

Marine Vibrator (MV) systems are technically not commercially widely available yet, and thus could not truly be called a Best Available Technology. MV has been in development since 2008 so it is surprising that its progress has been so slow. Still, this technology remains promising. If regulators were to insist on use of quieter alternatives to airguns, it is likely these would be available very quickly, but regulators feel they cannot require a technology that is not available yet, so it becomes a Catch-22. The seismic industry also does not feel like it is incentivized by regulations to pursue quieting technologies. Seismic vibrators have been used successfully in land-based seismic exploration for many years. In 2009, when the Okeanos Foundation held a workshop entitled "Alternative Technologies to Seismic Airgun Surveys for Oil and Gas Exploration and their Potential for Reducing Impacts on Marine Mammals", the 16 participants (geophysical scientists, seismologists, biologists, and regulators) concluded that controlled sources such as marine vibrators probably offer the best chance at eventually replacing airguns (Weilgart 2010).

Tenghamn (2006) introduced a completely new electro-mechanical MV concept, using frequencies from 6 to 100 Hz. Pramik (2013) reported that, as MV is a scalable source, output level can be adjusted in real time to environmental and operational conditions. MV output can be changed by altering the number of vibrators used in the array (more difficult with airguns due to undesirable acoustic side effects), by changing the output level, and by changing the length of the sweep (Pramik 2013). With MV, the emitted frequency band, phase, amplitude (loudness--SPL), or energy over time (SEL) can be selected, something which is largely impossible for airgun surveys. The controllable nature of the MV source could also bring advantages in signal processing. Phase and amplitude control could allow sources to improve the reconstruction of the wavefield between source lines with less shots acquired and faster acquisition. The amplitude

Picture 6. 18 liter air gun, secured for Arctic transport aboard the R/V Sikuliaq. © Sonobuoydude/Wikipedia Commons

and phase control also allows for a more effective reduction in residual noise. Additionally, MV produces no cavitation. The initial capital cost of the MV array is large, but the operational cost is similar to airguns, with geophysical and operational benefits (Amar et al. 2020, Jenkerson et al. 2018, Laws et al. 2019). It works best from 5-100 Hz.

Because of the need to better control the output of marine seismic sources and to reduce their environmental footprint, TotalEnergies, ExxonMobil and Shell have sponsored the Marine Vibrator Joint Industry Project (MV JIP) since 2011, supporting the development of three separate marine vibrator technologies. Currently, the MV JIP is working exclusively with APS to develop and commercialise the Integrated Projector Node (IPN) powered by an electromagnetic system.

The only MV technology to have acquired seismic data as part of a pilot project are the HUP104 unit developed by Mobil, Total and Geco in 1996 at Schooner Bayou, Louisiana, and the SAE developed Aquavib™ Marine Vibrator which acquired a series of 2D lines in Louisiana (Pramik et al. 2015) as well as east offshore Malaysia in 2019. The Aquavib™ technology is currently in production targeting transition zones. It works better in water depths less than 5 m than airguns do.

Shearwater, with the support of the Norwegian Research Council and Equinor, are also developing the BASS (Broadband Acoustic Seismic) Source MV which is a hydraulic based system. No official information has been provided on the timing of a possible commercialisation by them, but the current understanding is that they will also be ready to conduct a pilot project in Q1 2023.

Most airgun arrays have an effective source level of 255 dB (0-p) re 1 μPa at 1 m in the downward direction, compared with a MV array of about 223 dB rms re 1 μPa at 1 m (Bird 2003) or about 226 dB (0-p). Since the decibel scale is logarithmic, MV has a peak pressure that is a factor of 28 lower than that of the airgun array. LGL and MAI (2011) estimated that a MV survey would expose only about 1–20% of whales and dolphins to ≥180 dB re 1 μParms when compared to those exposed to an airgun survey, based on their models. Matthews et al.'s (2021) desktop modelling comparison of potential effects on marine mammals from MV vs. airgun noise also concluded that injury was less likely from MV arrays. High peak pressure and sharp rise time or onset (sounds quickly increasing in amplitude), both of which describe airgun emissions, are two characteristics of sound thought to be particularly injurious to living tissues (Southall et al. 2007). Southall et al. (2007) believe a non-impulsive sound such as MV would have to be 12–17 dB louder than an airgun-like impulse to cause the same degree of injury, due to the damage inflicted by the sharp rise time. Additionally, Duncan et al. (2017) modelled sound levels from a realistic MV array and airgun array with similar downward energy at frequencies < 100 Hz and compared the two under various scenarios. They found that at a 100 m range, MV was 20 dB lower in peak-to-peak sound pressure level vs. the airgun array, decreasing to 12 dB lower at a distance of 5 km, the maximum modelled range for peak levels. MV also produced 8 dB lower SELs than the airgun array at 100 km range because of MV's reduced bandwidth (Duncan et al. 2017). Thus, there are benefits to MV even at long ranges and even for animals with good low-frequency hearing. Duncan et al. (2017) also found that changing the layout of the MV array's higher frequency sources reduced sound exposure levels by 4 dB. MV's lower SEL advantage is most obvious in shallow water, as SELs drop off more rapidly in these waters. In addition, shallow waters are often the most productive and biologically rich, in need of more protection.

In summary, Duncan et al (2017) listed the main benefits of MV over airguns as:

- Lowering peak pressure (sound level) over short ranges
- Eliminating sharp rise time
- Eliminating unnecessary middle and high frequencies
- Lowering Sound Exposure Levels for distances of over 10 km
- Allowing for greater control and tailoring of the signal (amplitude, frequency, duration, etc.) in real time
- Operationally superior in shallow water and transition zones

MV thus shows potential in providing an environmentally safer alternative to airguns without compromising effectiveness for seismic exploration. LGL and MAI (2011) state that MV surveys would be expected to cause less of an impact (behavioral, physiological, auditory) than airgun surveys in all habitats and environments regardless of water depth or environmental conditions. The approximately 20 dB reduction in short-range peak-to-peak pressure levels decreases the safety or exclusion zone radius by roughly a factor of ten, translating to a reduction in safety zone area of about a factor of one hundred, which could greatly reduce the number of animals exposed to sound likely to cause injury.

The greatest drawback of MV compared with airguns is the greater potential for masking, since the MV signal is of longer duration (seconds vs. tens of milliseconds for an airgun pulse), and MV will likely have a higher duty cycle (percentage of time it is "on"). Some estimates of MV signal duration range from 5-12 s (LGL and MAI 2011). This would impact mainly low-frequency hearing specialists such as baleen whales and some fish. Slight masking effects could extend to a few tens of kilometers from the MV source. Using narrow-band FM sweeps as the MV signal would likely ameliorate the potential for masking (LGL and MAI 2011). Moreover, airgun pulses are also not always as short in duration as they appear, if heard over larger distances from the source. Reverberation and multi-paths "stretch" the signal from its original 10 ms to sometimes seconds at long ranges (Guerra et al. 2011). Sometimes, noise levels do not have a chance to return to ambient in the 10 s between airgun shots, since there is still reverberation from the previous shot (Guerra et al. 2011). MV signals can also be lengthened or stretched in time with increasing distance from the source, but such stretching would be proportionally less than for airgun pulses, since MV signals are longer in duration initially, close to the source (LGL and MAI 2011). Importantly, MV signals would likely fade more quickly into the background ambient noise levels.

The Joint Industry Program on E&P Sound & Marine Life (SML JIP) have issued a Request for Proposals to determine the environmental impact of prototype MV technology. Of interest is the impact of MV output signals on marine mammal auditory masking and behavioral responses. The current intention of the MV JIP discussed above is to provide two MV units for two behavioral response field trials (in Q3 2023 and Q3 2024, respectively, in California). MV should be field-tested for impacts on a wide range of sensitive marine taxa, something which should ideally happen in tandem with operationally testing various MV designs. As with other noise-reduction measures from seismic surveys, the development of MV could be greatly expedited with encouragement and pressure from regulatory governmental agencies (Duncan et al. 2017).

Monitoring technology

To assess the population density, abundance, and distribution of marine life before, during, and after seismic surveys, monitoring, especially ahead of time, of the proposed survey area should be carried out with fixed acoustic detectors (buoys, bottom recorders, etc.) or mobile gliders. Gliders can be used both for vocal marine mammals and fish species.

Infrared (IR) or thermal imaging shows promise in detecting warm-blooded marine life, such as whales and dolphins, which can help in nighttime monitoring, especially of baleen whales (Zitterbart et al. 2013). It is not meant to replace Marine Mammal Observers but to supplement them by alerting them to possible whale blows (exhalations). It also does not function well in some conditions, such as fog, or with species that do not spend much time at the surface or with obscure blows (Zitterbart et al. 2013). It does not work well on smaller whales, even ones the size of minke whales, and is very expensive. It seems to work best in polar regions.

Passive Acoustic Monitoring (PAM) should be used anytime there are vocal species in the area, during daytime or nighttime. Towed arrays or other suitable technologies with enough bandwidth to be sensitive to the whole frequency range of animals expected in the area should be used to improve detection capabilities. PAM should be mandatory for night operations or when visibility is scarce. However, PAM may be inadequate mitigation for night operations if species in the area are not vocal or easily heard.

1.4 BEP for Seismic Airgun Survey Noise

As mentioned above, probably the most effective mitigation for seismic airgun surveys is to: a) separate the seismic surveys from areas rich in marine life and sensitive species; and b) to lower the source level (quiet the noise). To separate seismic surveys from marine life, however, there must be good, current knowledge of the abundance and distribution of that life. Therefore, baseline studies of biological abundance and distribution must occur at least a year, preferably two, in advance of seismic surveys. These must be of sufficient quality and statistical power to detect changes in abundance and distribution of marine life over natural variation. Sensitive and important habitats and seasons (spawning, breeding, feeding, etc.) should be avoided, and not just for marine mammals. Turtles, fish, and invertebrates must be included in mitigation and monitoring wherever possible. Acoustic refuges of still quiet habitat should be established, and Marine Protected Areas should be managed for noise and include acoustic buffer zones around them, considering the possible impact of long-range noise propagation. Seismic airgun surveys should avoid acoustic refuges and Marine Protected Areas.

The ACCOBAMS (Agreement on the Conservation of Cetaceans in the Black Sea, Mediterranean Sea and contiguous Atlantic area) Resolution 7.13, Guidelines to Address the Impact of Anthropogenic Noise on Cetaceans in the ACCOBAMS Area, are very close to BEP for seismic airgun survey noise. Where new mitigation measures not contained in the Resolution have been added, these are marked as “NEW”. ACCOBAMS is only focused on cetaceans, whereas this document is concerned with all marine species and overall ecosystem health, so sometimes more mitigations, or the present mitigations slightly modified, are considered necessary. There are other worthwhile mitigation measures in the Resolution that are not included here in the interest of brevity. The Resolution also contains guidelines to address noise from shipping and from coastal and offshore construction works, such as pile driving, but these, while very valuable, are either not as current or detailed as those outlined in this report, whereas those for seismic surveys are especially extensive. Hence, only the “guidelines for seismic surveys and airgun uses” are included here:

1. Baseline studies of biological abundance and distribution of sensitive species, including turtles, fish, and invertebrates, must occur at least a year,

Picture 6. Seismic blasting off North-East Greenland. The air guns emit 259-decibel blasts towards the seabed in order to find possible oil reservoirs. © Christian Aslund/Greenpeace

preferably two, in advance of seismic surveys. These must be of sufficient quality and statistical power to meaningfully mitigate impacts. (NEW).

2. Seismic surveys should be planned to avoid key habitat and areas of density of marine life, so that entire habitats or migration paths are not blocked, so that cumulative seismic noise is limited within any particular area, and so that multiple vessels operating in the same or nearby areas at the same time are specifically regulated or prohibited.
3. Seismic surveys should not be allowed to proceed without some proof of efficacy of the mitigation measures used and for all sensitive species. (NEW).
4. Acoustic refuges of still quiet habitat should be established (NEW), and Marine Protected Areas should be managed for noise and include acoustic buffer zones around them, considering the possible impact of long-range noise propagation.
5. Transparent, public notification of when and where seismic surveys will take place as soon as this is known by the operators (months in advance). (NEW).
6. Use of the lowest practicable source power and (NEW:) have this verified by independent evaluators.
7. Limit horizontal propagation by adopting suitable array configurations and pulse synchronization and eliminating unnecessary high frequencies.
8. Airguns should not be operated for any reason outside the permitted project area. (NEW).
9. Adapt the sequencing of seismic lines to account for any predictable movements of animals across the survey area and avoid blocking escape routes.
10. Modelling of the generated sound field in relation with oceanographic features (depth/temperature profile, water depth, seafloor characteristics) to dynamically set the Safety or Exclusion Zone (EZ). Verify models of the EZ in the field. (NEW:) EZ should be at minimum 500 m but may be larger depending on the propagation.
11. Continuous visual and passive acoustic monitoring (PAM) by a specialized team of Marine Mammal Observers (MMOs) and PAM operators to (NEW) reduce the risk that animals are in the Exclusion Zone before turning on the acoustic sources and while sources are active (The original wording was "...operators to ensure that animals are not in the Exclusion Zone...").
12. Equipment for visual monitoring should include suitable binoculars and big eyes to be used according to the monitoring protocol.
13. Airgun surveys should be prohibited at night, during other periods of low visibility, and during significant surface-ducting conditions, since mitigation tools are likely inadequate to detect and localize sensitive marine life. Because of the impact of adverse weather

Picture 7. Marine turtles, like this critically-endangered hawksbill turtle (*Eretmochelys imbricata*), are also sensitive to underwater noise. © Canva.com

conditions on the visual detection of animals, seismic surveys during unfavourable conditions ((NEW:) over Beaufort Wind Speed of 3) should be prohibited as well. (NEW:) Only if Passive Acoustic Monitoring (PAM) is proven as effective in detecting sensitive marine life as PAM together with MMOs, should seismic surveys in poor visibility and at night be allowed.

14. Passive acoustic monitoring (PAM) (towed array technology or other suitable technologies with enough bandwidth to be sensitive to the whole frequency range of sensitive marine life expected in the area) should be used to improve detection capabilities. PAM may be inadequate mitigation if animals in the area are not vocal or easily heard.
15. At least two dedicated Marine Mammal Observers (MMOs) should be on watch at one time on every operative ship; shifts should be organized to allow enough rotation and resting periods for MMOs. In the case of acoustic monitoring, at least one PAM operator should be on watch and shifts should be organized to allow 24/24h operation, unless automatic detection/alerting systems are proven to be as effective as PAM operators. Standardized tests (written and in the field) for MMOs and PAM operators, used worldwide, should be developed to ensure MMOs and PAM operators pass standard qualifications.
16. Before beginning any emission there should be a dedicated watch of at least 30 minutes to reduce the risk that animals are within the EZ.
17. Establish a minimum pre-clearance zone (i.e., pre-ramp up watch zone) that extends 500-1000 m from the outer perimeter of the airgun array(s). (NEW).
18. Extra mitigation measures should be applied in deep water areas if beaked whales are expected or if habitats suitable for beaked whales are approached: in such cases, the watch should be at least 120 minutes to increase the probability that deep-diving species are detected.
19. Every time sources are turned on, there should be a slow increase of acoustic power (ramp-up or soft start) to increase the chances that animals might leave the ensonified area (the effectiveness of this procedure is still debatable).
20. The beginning of emissions should be delayed if sensitive species are observed within the exclusion zone (EZ) or approaching it. Ramp-up may not begin until 30 minutes after the animals are seen to leave the EZ or 30 minutes after they are last seen (120 minutes in case of beaked whales).
21. There should be a shut-down of source(s) whenever a sensitive species is seen to enter the EZ and whenever aggregations of vulnerable species (such as beaked whales) are detected anywhere within the monitoring area.
22. If more than one seismic survey vessel is operating in the same area, they should maintain a minimum separation distance (dependent on propagation) to allow escape routes between sound fields.
23. Data sharing among seismic surveyors should be encouraged to minimize duplicate surveying. Also, if old seismic data can be usefully re-analyzed using new signal processing or analysis techniques, this should be encouraged. (NEW:) Duplicated surveys need to be justified.
24. A quantitative analysis of cumulative and synergistic impacts not just of noise but of all anthropogenic threats over time should be conducted as part of a thorough Environmental Impact Assessments (EIAs) following the CMS Family Guidelines on EIAs for Marine Noise-Generating Activities, including consideration of historical impacts from other activities (shipping, military, industrial, other seismic) in the specific survey area and nearby region. Databases and noise registries should be developed to allow such analyses. (Addition of CMS Family Guidelines and synergistic impacts is new).
25. A system of automated logging of acoustic source use should be developed to document the amount of acoustic energy produced, and this information should be available to noise regulators and to the public.
26. Mitigation should include monitoring and reporting protocols to provide information on the implemented procedures, on their effectiveness, and to (NEW:) improve data on biological abundance and distribution, as well as to examine impacts from seismic survey noise. Monitoring should be proven to be statistically powerful enough to detect subtle impacts, strandings, fish kills, etc. BDA (Before During After) or BACI (Before After Control Impact) studies to examine impacts must also contain power analyses to show whether possible impacts would be detectable or not. Impact and biological baseline studies should include more fish, turtles, and invertebrates. All biological and impact data collected for mitigation should be publicly available.
27. MMO and PAM reporting should be standardized so that data can be harmonized across all seismic surveys worldwide for maximum statistical power. (NEW).
28. During operations, existing stranding networks in the area should be alerted; if required, additional monitoring of the closest coasts and for deaths at sea should be organized.
29. A biological survey after the seismic survey is finished should be carried out to verify if changes in the abundance or distribution of species or anomalous deaths occurred.
30. In the case of strandings, deaths at sea, or abnormal behavior possibly related with the operations, any acoustic emission should be stopped, and maximum effort devoted to understanding the causes of the deaths or abnormal behavior.

1.5 BAT for Pile Driving Noise

Noise levels

Impact pile driving is the most common method of foundation installation for offshore windfarms and other structures such as piers and bridges. Pile-driving using a hydraulic hammer with an energy of 1000 kJ results in sound levels around 237 dB re 1 μPa at 1 m. The noise generated has a predominant bandwidth of 100–1000 Hz (Hildebrand 2009), but it also extends beyond this range into the tens of kHz. Currently used hydraulic hammers have a rated energy range of up to 4000 kJ which increases noise emissions further, also with increasing pile size.

Impacts

Due to the wide frequency range of underwater piling noise, a broad range of marine life can be affected by the activity. Specifically, the harbour porpoise avoids pile driving out to a mean distance of 17.8 km. At 22 km, this avoidance was no longer apparent. Porpoise activity and possibly abundance were reduced over the entire 5-month windfarm construction period (Brandt et al. 2011). After cessation of piling noise, it can take up to two days until harbour porpoise behaviour returns to pre-piling conditions (Brandt et al. 2016). Blue mussels (Roberts et al. 2015, Spiga et al. 2016) and seabream (Bruintjes et al. 2017) showed signs of stress from pile driving. Swimming and schooling behaviour was also affected by piling in cod and sole (Mueller-Blenkle et al. 2010), sprat and mackerel (Hawkins et al. 2014), and juvenile seabass (Herbert-Read et al. 2017).

Underwater noise limits

Largely due to the German government setting an action-forcing standard for better systems, major progress in quieting technology has been made for pile driving. In 2004, The German Federal Maritime and Hydrographic Agency introduced noise guidance values for single strikes of 160 dB re 1μPa^2 s (SEL) and maximum 190 dB re 1 μPa (peak) at a distance of 750 m in the licenses of offshore wind farms within the German EEZ. In 2008, these became mandatory and were successfully applied in 2013, reaching state-of-the-art reliable compliance despite increasing pile diameters and water depths through 2018. No offshore windfarm in German waters has since been constructed without complying with these underwater noise limits. In 2013, the German Federal Ministry for the Environment also published its Sound Protection Concept. In addition to technical mitigation measures, pile driving companies purposely use lower piling/hammer energies to stay under the German noise limits.

A growing number of countries across Europe, Asia, and North America are following Germany's lead and now also impose underwater piling noise restrictions during OWF (Offshore Windfarm) construction. These noise restrictions differ between countries, e.g., with respect to the noise level allowed, the use of frequency weighted or unweighted levels, or the use of single strike or cumulative levels integrated over the duration of a piling operation. These can take project-specific (e.g., number of strikes depending on hammer energy used) as well as species-specific aspects (e.g., hearing curves) into account. It is also often observed that newly developed regulations in some regions are challenging, if even possible, to monitor in real time during installation. Being able to monitor regulated activities in real time against enforced thresholds is important for ensuring correct decisions are made during installation (e.g., hammer energy selection or choice of noise abatement systems). With such a practical framework, it is more likely that operations will comply with local regulations, ultimately reducing the risk of harming marine life.

Noise mitigation and abatement systems

Noise Mitigation Systems (NMS) work to avoid or reduce the noise inputs into the water whereas Noise Abatement Systems (NAS) function in reducing the impact of existing pile-driving noise already in the water. Koschinski and Lüdemann (2020) detail technical noise mitigation measures for pile driving as well as alternative low-noise foundation concepts and analyze their applicability. Bellmann et. al. (2020) also provides a comprehensive overview of currently available noise abatement systems as well as a thorough explanation of underwater piling noise transmission and the factors that influence it. Using empirical datasets from the North and Baltic Seas, the report provides estimated noise mitigation levels for almost all NAS available on the market. The report finds the IHC Noise Mitigation Screen (IHC-NMS) the most effective near-pile mitigation system available, estimating reductions in sound exposure levels of up to 17 dB. When combined with an optimized Double Big Bubble Curtain (DBBC), reductions increase further up to 22 dB in water depths of 40 m. They discuss a broad range of site-specific influencing factors such as soil parameters, water depth, bathymetry, sound propagation, and measuring details.

Another recent report was provided by Verfuss et al. (2019) who reviewed NAS for OWF construction noise and how applicable these were for Scottish waters. The report (Verfuss et al. 2019) provides:

- "A description of the status of currently commercially available and frequently used NAS and those under development;
- A summary of the experience of NAS users and NAS providers with regard to the logistical requirements

Picture 8. The harbour porpoise *(Phocoena phocoena)* is a species highly sensitive to underwater noise that inhabits many areas used for wind farm developments. © Canva.com

and limitations for the deployment and operation of these NAS;

- A review of the environmental limitations that may influence the deployment and operation of NAS;
- A review of the direct cost implications associated with the use of NAS;
- A review of the noise reduction efficacy of NAS, specifically with reference to the marine species inhabiting Scottish waters."

The main findings of Verfuss et al. (2019) were that:

- Big Bubble Curtains (BBC), the IHC Noise Mitigation System (IHC-NMS), the Hydrosound Damper (HSD) and vibrohammers (VH) have all been commercially deployed as NAS in OWF-projects;
- The AdBm-Noise Abatement System (AdBm-NAS) completed its full-scale test in 2018 and was planned to be deployed commercially in an OWF-project in 2019. The AdBm system was ultimately deployed for this project. However, very limited data on its acoustic performance were obtained during the project;
- Currently under development are BLUE Piling Technology (BLUE Hammer) and HydroNAS;
- With either the BBC, IHC-NMS or HSD, broadband sound levels can be reduced by at least 10 dB;
- The NAS are generally more effective at reducing the risk of noise impact on marine mammals and fish sensitive to higher frequencies than on fish that are only sensitive to frequencies below 100 Hz;
- VH is an NAS that has been applied in industrial projects in water depths prevailing in potential future Scottish OWF-sites (up to 77 m);
- BBC, VH, HSD and NMS are NAS that have been commercially deployed in OWF projects in water depths up to 45 m;
- BBC and VH have been used with monopiles and jacket foundations, while NMS and HSD have only been used with monopiles, except for one HSD-prototype test with jacket foundations;
- Field experience with the deployment of all NAS in OWF-projects at water depths beyond ~45 m is lacking. However, most are applicable in theory;
- Field experience with the deployment of NAS during the installation of piles with a diameter greater than ~8 m is lacking;
- Full knowledge on the drivability and bearing capacity of piles driven with BLUE Hammer is still lacking;
- There are perceived risks regarding drivability of piles using VH due to limited experience with the use of VH in OWF-projects;
- There are diverging opinions regarding the need to assess the axial bearing capacity of monopiles driven with VH.

Those abatement systems that can be considered Best Available Technology under certain circumstances and some of their limitations are described below.

Recently, piles with diameters of 9 m have been installed, compared with initial piles which were in the order of 2.5 m in diameter. 12 m-diameter piles are even proposed for the future. Different types of foundations are used for different substrates and water depths. Driven piles are typically founded in sandy soils, such as areas in the North Sea, whereas drilled piles require a higher substrate strength, though substrate strength could be high enough when the drilling gap is filled with a specific filling material. Site-specific calculations would be necessary to determine the method of installation.

It is important to note that during pile driving, the acoustic pressure wave can enter the substrate and re-emerge into the water column at a greater distance from the pile ("ground-coupling effect"). Thus, mitigating the noise emitted through the water near the pile (e.g., by deploying an HSD, AdBm or IHC-NMS system) may not be sufficient. For this reason, Big Bubble Curtains (BBCs) can be highly effective, as they can mitigate noise that re-enters the water column at distances up to 150-160m from the pile. NAS can be categorized as near-pile or far-field systems, and to ensure sufficient mitigation is achieved, it may be required in some circumstances to deploy both a near-pile and a far-field system.

Primary noise reduction, occurring at the source, also has the advantage of solving this substrate transmission problem. Secondary noise reduction occurs once the sound has already been transmitted into the water or substrate. The most effective way to reduce noise at the source is to use a foundation that does not require impact pile driving such as, e.g., gravity based, bucket, drilled or floating foundations.

Vibropiling

Vibration pile-driving, or vibropiling, could be a promising alternative to conventional pile driving as it avoids impulsive sound. The advantages include lower (but continuous) noise levels, faster installation (and therefore less exposure time), material saved on the monopile and less mitigation for noise (based on current regulations). There is also considerable offshore experience using vibropiling. First full-scale installations have recently taken place in the OWF Kaskasi 2 in the German Bight (https://ocean-energyresources.com/2022/04/28/cape-hollands-vlt-completed-work-at-kaskasi-ii-owf-video/). Noise measurements are not available yet (as of July 2022). Monopiles were, however,

Picture 9. BLUE Piling is a new technology being tested and employed to reduce both underwater noise and material fatigue. © iqip.com

not vibrated to end depth (https://capeholland.com/news/cape-hollands-vlt-completed-its-work-at-kaskasi-2-owf/) due to technical problems, which makes this installation method somewhat experimental. Vibration piling is 10-20 dB lower in peak levels compared to mitigated pile driving. Levels fall to 140 to 145 dB in 8 km for pile driving vs. 1.5-3 km for vibropiling. The area in which these levels are exceed is thus 7-28 sq km for vibropiling vs. 201 sq. km for pile driving. However, vibropiling causes very low frequencies so further mitigation using a bubble curtain would not reduce the noise substantially. The noise peaks arise from rattling from the loose connections of the vibrohead. While vibropiling may reduce peak noise levels, the continuous noise source is likely still problematic for marine life, since the low frequencies radiating from the source can affect especially seals, baleen whales, and fish which all have good hearing at these frequencies and use them for communication and other functions.

BLUE Piling

The BLUE Piling hammer replaces the typical steel ram weight of an impact hammer with a large water mass. The resulting blow is considerably longer in duration than a conventional impact hammer, which reduces underwater noise and material fatigue. The pile can be considered to be more “pushed” rather than driven, but in principle, the technology uses the same methodology as a conventional impact hammer. It is expected that there will be less stress on the hammer and no bending or stress fluctuations in the steel. As a result, this could be a cheaper alternative, reducing both fatigue and potentially the need for costly noise mitigation systems. Operating the hammer on a large enough scale suitable for large monopiles still needs validating.

Adaptation of Hydraulic Hammers

By incorporating an adjustable cushion between the ram weight and anvil of either steel or water, the impact force can be prolonged, and the amplitude reduced. This can result in a sound exposure level reduction on the order of 4 to 6 dB (Koschinski and Lüdemann 2020), while also achieving up to 60% reduction in fatigue and stress on the equipment. Reducing the amplitude of the peak force can, however, result in premature refusal, i.e., when five or more blows of an adequate hydraulic impact hammer will not budge the pile, as the peak driving forces may no longer be sufficient to overcome the soil resistance. This can then require continued operation without this add-on to the hammer or using a higher energy which, in both cases, would increase the radiated underwater noise.

The Menck Noise Reduction Unit (MNRU), which is in use for the first time on the Greater Changhua OWF in Taiwan, incorporates a steel cushion block. The IHC-PULSE, currently being developed by IHC, uses a cushioning chamber filled with water. If premature refusal occurs due to insufficient peak forces, the water in the IHC-PULSE system can be drained within minutes and the system operated as a conventional hydraulic hammer to achieve greater peak forces. Since the piling cushion is inside the hydraulic hammer, it can be combined with other noise mitigation methods for impulsive piling.

Smart Pile Driving

With sufficient engineering preparation and the assistance of online noise monitoring, a piling approach can be followed to minimize noise levels. By optimising hammer energy and blow frequency in line with real-time noise measurements, noise levels can be reduced while ensuring the pile continues to penetrate at an acceptable rate. By reducing hammer energies and increasing blow frequency, single-strike noise levels will decrease. By halving the hammer energy, the SEL can be reduced an additional 2.5 dB. An optimised approach is, however, important, as well as selection of a suitable hammer. If the driving energy is too low the pile will not penetrate, yet if the energy is too high, unnecessarily high noise levels may be generated. Also, to reduce the energy, a larger number of strikes would be required which might reduce the single strike SEL but not decrease the cumulative SEL which is required by some regulations, and which is one factor to consider when auditory injury is to be avoided.

Bucket Foundations

Suction Caisson/Bucket Foundations are used for low substrate strength (sandy soils, clay or combinations thereof), and a relatively flat seabed is preferable; little seabed preparation is required. The structure can be installed without the use of any mechanical force. Suction pumps inside the buckets generate a pressure difference between the inside of the upside-down positioned bucket and the hydrostatic pressure at the seabed, and the structure sinks into the soil by its self-weight. The noise barely exceeds background levels. If obstacles such as large boulders are discovered during installation and at the end-of-life, the procedure can be reversed, and the structure retrieved. Suction caissons were originally developed for deeper waters for oil and gas applications. Due to the low hydrostatic pressure needed to stabilize the structure, there are installation challenges in very shallow water (water depths < 20m). A lower length-to-diameter ratio (and thus a larger “footprint”) compared to their deep-water use allows applications for OWFs in shallower water (<100 m).

There are two types of bucket foundations, Suction Bucket Jackets (SBJ) and Monobucket foundations.

In SBJs a number of buckets are connected rigidly to a welded framework structure whereas the monobucket foundation is a monopile foundation with a suction bucket-seabed interface. SBJ can be used in many substrate conditions, but not very hard soils, soft soils, or rocks. Also, high seabed mobility and loss of substrate could compromise the stability. There is an impact on soil and benthic biotypes. 32 three-legged suction bucket jackets have successfully been installed between 2014 and 2020 at water depths ranging from 23 to 29 m. A monobucket was successfully installed in a polder in Fredrikshavn (Denmark) (Koschinski and Lüdemann 2020).

Gravity-Based Foundations

Gravity-based foundations are reinforced concrete or steel/concrete hybrid structures whose stability is achieved by the submerged weight of the structure, supplemented by additional ballast (e.g., sand). They are most suitable for depths of up to 50 m. They can also be designed for deeper waters and have been used extensively by the oil and gas industry in depths of up to 300 m, bedrock, consolidated sediments, and areas with large, buried boulders. Their disadvantage is that they may have a relatively larger impact on benthic life, since at least some types remove the upper layers of the seabed, and their footprint area is larger than that of a monopile.

Crane-free gravity foundations are an example of a noiseless foundation. Dredging is usually not required, and they do not cover much of the seabed, though more than conventional foundations. It is proven technology and is inexpensive. It is more cost-effective at larger depths and bigger turbines compared to other foundation types. The foundations are self-floating so do not need cranes or large installation vessels. There is no sound emission from the subsea installation process, and no deep penetration of seabed. In current prototypes, the base diameter is 31-34 m. Two tow vessels (tugs) pull the vertical pile through the water, and they can be installed in seas up to 2 m. Installation is estimated to take 4 hrs. Once on position, the foundation is deployed by filling the hollow foundation with seawater. After it is resting on the seabed it is filled with ballasting weight of sand or gravel, fixing it to the seabed. Ballast is used so the foundation can withstand high turbine and wave loads. The foundation is placed on a filter layer with scour protection. Additional skirts at the base improve load resistance, reduce overall dimensions, avoid dredging, and reduce weight. Gravity-based foundations can be designed for lifespans of 50 years or more. They require a minimum water depth of 10 m.

Drilling

There are several offshore foundation drilling techniques for various substrate conditions.

1. BAUER MIDOS-Pile combines mixing and drilling technology to install a structural pile. The drilling and mixing tool is full of grout. This can be used in mainly sandy substrates but also clay and rock. The substrate is mixed with cement and creates a slurry that is injected during drilling. The structural capacity is higher so shorter and smaller piles can be used. XXL monopoles are too big for this technology, however. There was considerable bearing capacity when tested in loose, silty, sandy soil. The noise is much lower than piling and the structural capacity is better. The substrate must be mixable, e.g., sand with some clay.
2. BAUER Dive Drill Technology is used for the installation of drilled and grouted piles. Drilling occurs inside a casing and is replaced with the pile. A temporary casing is installed using the Bauer Dive Drill. Once the borehole is finished, the pile is installed, grouted, and then the temporary casing is recovered. Dive Drill Technology installs piles in fully cased boreholes and is suitable for all soil conditions including hard rock. It makes pile driving in marginal soil unnecessary.
3. BAUER BSD 3000 is for drilling piles in rock. The pile is installed and grouted afterwards. In 200-300 m, the noise is under background noise (125 dB rms).

Push-in and helical piles

Push-in and helical piles are two concepts for silently driven piles. Both concepts can serve as an alternative for jacket foundation piles and are therefore suitable for deep water wind turbine foundations. Both have been proven onshore. The push-in pile foundation uses a static force to drive piles into the seabed, and the helical pile foundation uses a rotating motion to drive piles fitted with several helical blades into the soil. Helical piles don't need to be as long and have shallow penetration. Both concepts are fully silent but will require special tools and in the case of the helical pile, an interface with the installation vessel using Dynamic Positioning.

Floating wind turbines

Many waters are too deep for non-floating structures. Floating turbines can be used in all different sediment types. The anchors are fully retrievable, and no effect on marine life has been observed in a prototype wind farm, WindFloat, off the Portuguese coast. The effects of anchors, however, may depend on anchor type. Different anchor types such as gravity anchors, suction buckets or drilled or driven piles can be used to hold the floating substructure and the wind turbine on top in place. Suction buckets are used most often as anchors. Drag anchors impact the seabed, though they are quiet. Further, there are some concerns with respect to a high number of vertical mooring lines in important habitats for baleen whales, which could cause harmful collisions.

There are three types of floating wind turbine platforms:

1. Float-stabilized structures or barges;
2. Tension Leg Platforms (TLPs);
3. SPAR buoys.

For 1., float-stabilized structures (semi-submersibles), the platform is floating and anchored to the seabed by cables which, in combination with ballast water, provide stability. Semi-submersible floating wind turbines have been deployed in some of the roughest seas of the Atlantic where they survived 17 m waves. Just one tug is needed to place the turbine, and it can be towed up to 500 km.

For 2., TLPs, the wind turbine rests on a platform supported by a number of cables anchored to the seabed. The cables are tensioned to stabilise the platform by counteracting its buoyancy and to maintain position of the turbine under any type of load. A TLP emits minimal noise. It is best used in >20 m water depth. To gain stability, TLPs require a fixed connection to the seabed which is under tension due to the buoyancy of the floater. Mooring cables come in various types (taut leg, tension leg mooring, etc.). Special vessels like jack-up barges are not required. Only small tugboats are needed, and then either one ballast gravity anchor with 4 pre-installed cables is dropped to the seabed or the structure is fixed to the seabed by means of drag, suction, or gravity anchors for each mooring line. There is little assembly time, a one-step installation, and little seabed preparation is necessary.

For 3., SPAR buoys, the wind turbine is supported on a long concrete or cylindrical steel column, completely submerged, which is ballasted at the bottom to stand upright and to provide stability and withstand loads produced by the wind and waves. These are used for deep-water applications.

Secondary noise mitigation

There are currently multiple near-pile NAS on the market compared with far-field systems. Examples of secondary noise reduction include:

1. A Big Bubble Curtain (BBC) consists of a large, perforated pipe positioned around the construction zone. Air is pumped through the hose from both sides using a number of compressors and is released through the perforations delivering a continuous flow of bubbles around the periphery the construction zone. From industry experience, BBCs can reliably provide an enclosed ring up to a length of 1000 m (approx. 160 m radius if deployed in a circular layout). Due to the large distance from the pile, BBCs are not limited to the size of the pile being installed. BBCs are extremely effective as they can attenuate acoustic energy that re-enters the water column from the seabed, which is one of the common disadvantages across all near-pile systems. For additional mitigation, two BBC hoses can be deployed in concentric circles spaced at least the water depth apart, forming what is known as a Double Big Bubble Curtain (DBBC). The use of (D)BBCs is independent of foundation design and installation vessel. The noise reduction depends on the air supply, water depth, subsea soil conditions, and current/direction/shape. Thus, each deployment needs to take project specific considerations into account. With an air volume stream of 0.3 m3/min*m (relatively low), the noise reduction (change in SEL) for a single bubble curtain was 11-15 dB at 25 m water depth, but only 8-14 dB at around 30 m, and 7-11 dB at around 40 m (Koschinski and Lüdemann 2020), since the bubble size becomes too small under the pressure of greater depths. Such a loss in mitigation can be overcome by increasing the amount of air or combining it with near-pile mitigation systems like the IHC-NMS, HSD or AdBm (see below).
2. The IHC Noise Mitigation Screen (IHC-NMS) is a proven near-pile NAS previously applied on piles under 8 m in diameter (though it is being discussed in the context of 10 m diameter piles) and under 40 m water depth. This system is a double-walled steel pipe with an air gap between the two layers. A multi-layered bubble curtain is also used in the center around the pile. A disadvantage is the ground-coupling effects that are not mitigated. Noise reduction is independent of water depth. Noise reductions up to 17 dB SEL have been achieved in water depths up to 40 m (Bellmann et al. 2020). It has been used in hundreds of monopile installations.
3. Hydro Sound Dampers (HSD) consist of foam resonators affixed to ballasted nets. HSD baskets, consisting of a net sleeve, container, and ballast, are dropped down into water around the pile, which collapse back up once the pile is installed and the basket is returned. Noise reduction is independent of water depth and attenuation is predominantly in the low frequency ranges. HSD are customisable and thus allow tuning the frequency bands in which noise needs to be reduced by choice of resonator sizes. If the balloons are appropriately-sized, their resonant frequencies can align with the peak frequencies of piling noise or with frequency bands of best hearing in sensitive animals for optimum damping effects. Data from multiple OWF projects in Germany suggest the HSD nets reliably achieve reductions up to 12 dB SEL (Bellmann et al. 2020), despite preliminary noise modeling suggesting greater attenuation. Overall, the system works for water depths up to 40-60 m and pile diameters up to 8-13 m. It is easily adaptable, weighing very little, and is not affected by water currents. A disadvantage is still the ground coupling effects . Like the others, this technology

requires a project-specific design and has been used in hundreds of monopile installations.

4. The AdBm-Noise Mitigation System uses rugged Helmholtz resonators whose acoustic properties can also be modified or "tuned" to optimally reduce noise. The system consists of several layers of inverted air-filled chambers, whereby the arrays of each layer are sized according to the depth at which they will be situated during piling. These resonators simply need to surround the sound source, and once they are in place, the resonators will passively absorb the noise. Improvements to the system are being tested whereby the air supply to the chambers is constantly running, creating an additional small bubble curtain around the pile for further noise mitigation. The principle of this system is very similar to that of the HSD nets, and therefore it is also most effective in the low-frequency ranges. The system can theoretically work in water depths beyond 70 m (Verfuss et al. 2019). The system is kept in place for the duration of the pile installation process and is ready for offshore use. Although the AdBm Noise Mitigation System has been used for a full-scale OWF project, very limited data on its acoustic performance have been published.

Picture 10. Common dolphins (*Delphinus delphis*), like all cetaceans, rely on sound for foraging, communication and navigation, making them highly sensitive to marine noise. © Canva.com

1.6 BEP for Pile Driving Noise

Most of the mitigation for pile driving noise is through the use of quieting technologies (see the above section on BAT) which have a great potential to dramatically reduce the area and the number of animals impacted by the noise. Additional BEP can consist of some operational procedures related to the behaviour of animals such as deterrence by using Acoustic Deterrent Devices (ADDs) or a soft start to account for those animals remaining at risk despite noise reduction. However, there is some debate whether or how much marine life should be purposely displaced at the start of pile driving, or how effective ADDs or soft starts are. Not all animals respond to them as intended, as they may be motivated to remain in an area, despite harassment by noise, because of access to food or mates. FaunaGuard is one device that has been used since research showed pinger and seal scarers produced more displacement than was necessary. Most of this research was done on harbour porpoises. Another possibility is using the mitigated pile driving noise itself but initially at lower energy and/or repetition rate (ramp up or soft start) to give marine life a chance to flee from the area before more harmful levels of noise are generated. As with seismic surveys, MMOs and PAM operators can also be used to reduce the risk of exposing marine life to dangerous sound levels. Visual and acoustic monitoring should be used in combination 24 hours a day to maximize the probability of detection of wildlife, including at night and during periods of poor visibility. If this monitoring is deemed insufficiently effective, the pile driving should not be allowed during nighttime and periods of poor visibility.

Some examples of best practices for pile driving that have been developed in the United States for the highly endangered right whale are listed below. The full document is available at:

https://www.nrdc.org/sites/default/files/best-management-practices-north-atlantic-right-whales-during-offshore-wind-energy-construction-operations-along-us-east-coast-20190301.pdf

- Construction activities with noise levels that could cause injury or harassment in marine mammals must not occur during periods of highest risk for priority species;
- During construction, developers should commit to minimizing impacts of underwater noise on priority species to the full extent feasible through: (i) the consideration and use of foundation types and installation methods that eliminate or reduce noise; and (ii) the use of technically and commercially feasible and effective noise reduction and attenuation measures, including the use of the lowest practicable source level;
- Developers should commit to carrying out scientific research and long-term monitoring in lease areas to advance understanding of the effects of offshore wind development on marine and coastal resources, and the effectiveness of mitigation technologies (e.g., noise attenuation). Science should be conducted in a collaborative and transparent manner, utilizing recognized marine experts, engaging relevant stakeholders, and making results publicly available. Developers should coordinate with regional scientific efforts to ensure results from individual lease areas can be interpreted within a regional context and contribute to the generation of regional-scale data, which is required to address questions related to population-level change and cumulative impacts.

As noted above, the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) adopted the Sound Protection Concept. In it, in addition to the technical noise reduction systems required, the following are also mandatory:

- Modelling of sound level emission for each specific wind farm project;
- Restrictions regarding the maximum duration of a piling operation for a single pile;
- Restrictions regarding the maximum energy used to drive the piles;
- Application of deterrents and ramp-up procedure to avoid injury close to the piling operation;
- Measurement and documentation of SEL05 during the whole installation process. (The SEL05 percentile level is used as reliable and standardized evidence for compliance with threshold values and is the level exceeded 5% of the time over the total piling period to account for cumulative effects due to multiple blows for driving piles to final penetration depth);
- Monitoring of harbour porpoise activity in the vicinity of construction sites;
- Requirements regarding a maximum percentage of area which is allowed to be affected also with a reference to protected areas or areas and seasons of biological significance.

1.7 Conclusions

One of the difficulties in responsibly managing ocean noise pollution is the challenge in detecting the ecosystem and population consequences of underwater noise. There is sufficient evidence that impacts are occurring in at least 150 marine species (around 100 fish and invertebrate species alone—Weilgart 2018), but being able to ascertain exactly to what degree, in which contexts, for which species, and at what sound types and levels these impacts occur remains imprecise. Because of the large natural variability in ocean systems (e.g., in currents, prey availability, chemistry), detecting human-caused changes in ecosystems and populations in the first place is a daunting task. The ocean is not a controlled laboratory. On top of that, isolating changes that are solely due to ocean noise pollution and not other human-caused stressors such as climate change, overfishing, and toxins, is formidable.

As such, it makes more sense to take a more precautionary approach, one of simply turning down the volume of ocean noise pollution. Especially in cases where there are ancillary benefits of quieting, such as reducing greenhouse gas emissions by finding the overlap between greater efficiency and less underwater radiated noise in shipping, and by encouraging technological innovation through quieter technological alternatives to airguns and by quieting pile driving, efforts are likely more effective using this approach.

In this respect, it must be noted that the great variety of quieting technologies and noise abatement systems for pile driving is in stark contrast to the lack of innovation that is occurring for quieter alternatives to the seismic airgun, though more have emerged recently. This may be due to offshore windfarms being a relatively new development compared with seismic airgun surveys.

Government regulations limiting the noise emissions from offshore windfarm construction, mainly due to the noise-sensitive and protected harbour porpoise, certainly help. If regulators insisted on quieter alternatives to airguns, something that seems well within technological capabilities, this would also likely drive innovations. After all, explosions on land to search for hydrocarbons were replaced with Vibroseis because explosions were no longer acceptable to humans. If we value our life-sustaining oceans, we should provide them with the same care and protection.

Picture 11. The noise-related impacts of shipping, energy extraction and renewable energy production can be mitigated if Best Available Technology (BAT) and Best Environmental Practice (BEP) are consistently applied. © Canva.com

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Appendix

(ref. chapter 1.1, section on Technological quieting measures)

Quieting measures were categorized in four main areas:

1. Propeller noise reduction;
2. Machinery noise reduction;
3. Flow noise reduction; and
4. Other

Measures are reviewed in terms of:

- 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 table provides a summary of prediction methods for underwater radiated noise (Kendrick and Terweij 2019). Table reproduced with permission.

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

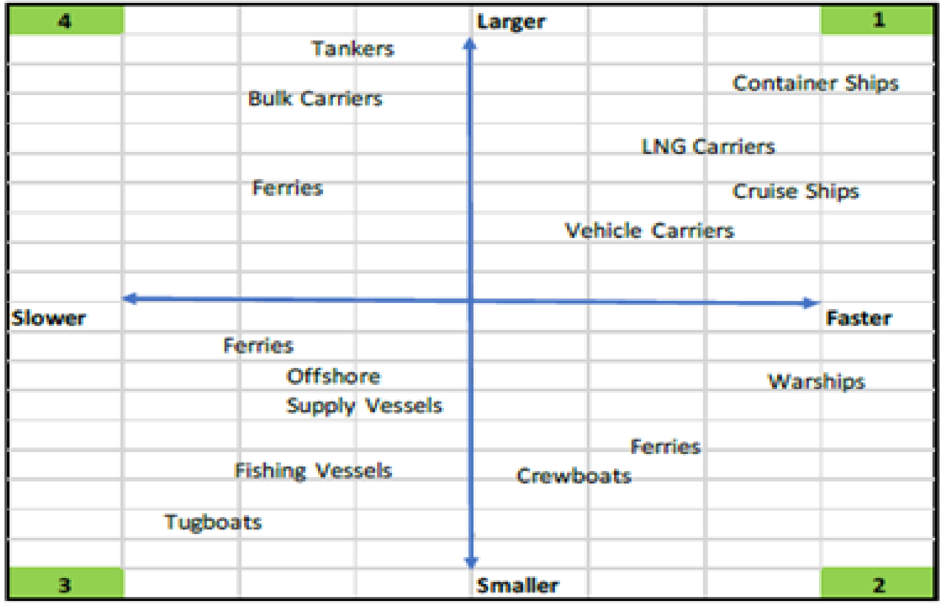
TRL - Technology Readiness Level

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

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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

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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**

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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

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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**

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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**

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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**

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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**

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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**

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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 m²**	**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 m² 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)
					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

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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

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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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