

PRACTICAL CONSIDERATIONS FOR
UNDERWATER NOISE CONTROL

FEBRUARY 2021



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INTRODUCTION

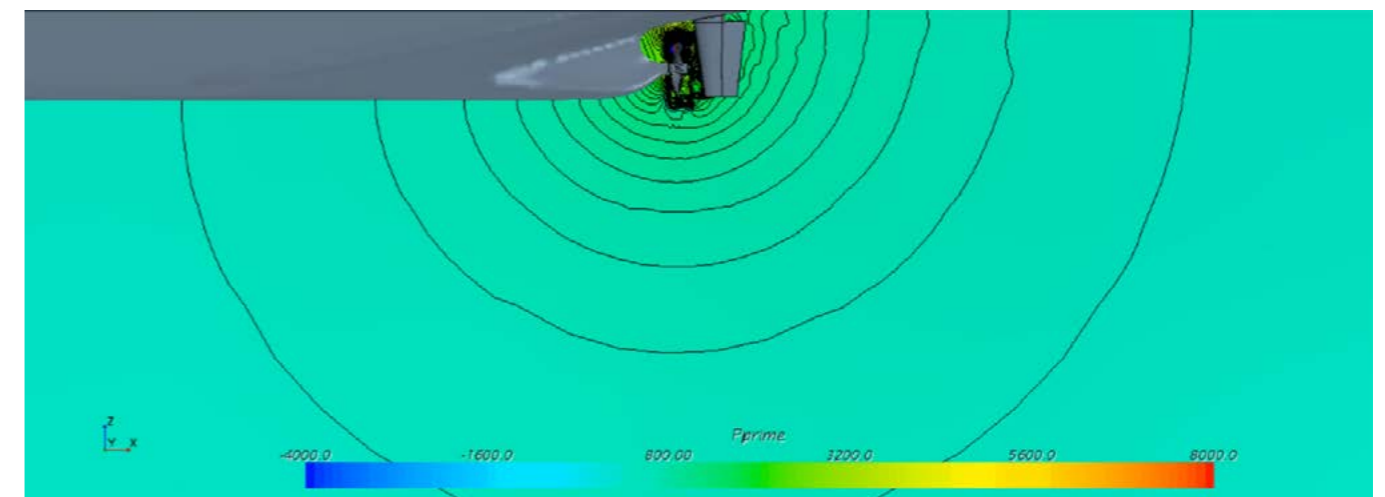
Underwater radiated noise emitted from commercial ships has attracted increased scrutiny in recent years, with studies indicating that sound generated by shipping contains high energy in the frequency range below 1,000 Hertz. This frequency range overlaps with the band that is critically important for marine animals and ecosystems and can cause the masking of their acoustic communications crucial for foraging, navigation, and ultimately even threatening their survival.

To encourage the reduction of the negative effects of underwater radiated noise on marine species, in 2014, the International Maritime Organization (IMO) published MEPC.1/Circ.833 Guidelines for the Reduction of Underwater Noise from Commercial Shipping to Address Adverse Impacts on Marine Life.

The European Union (EU) Marine Strategic Framework Directive, 2008/56/EC, which came into force in 2008, requires EU Member States to achieve a 'Good Environmental Status' in all the EU waters by 2020, including the reduction of underwater radiated noise.

In January 2019, a technical workshop, entitled Quieting Ships to Protect the Marine Environment, was held at the IMO headquarters in London, with over 140 participants from around the world. The workshop conducted a thorough review of the state of knowledge on 'quieter ship' design and contributed to several papers submitted to the IMO's Marine Environment Protection Committee (MEPC) in 2019 and 2020.

Classification societies have also increased their efforts to support the maritime industry in addressing this emerging demand, with optional classification notations offered to those ships designed and operated with consideration of the impact of underwater radiated noise.



ASSESSING UNDERWATER RADIATED NOISE

There are various sources of ship underwater radiated noise, with propeller-generated noise as one of the key items. Machinery equipment such as the main engine can also be an important contributor, especially at low vessel speeds. A less prominent yet still relevant source is water flow around the hull. Among various technical challenges for building quieter ships for commercial operation, research and technology development in recent years has primarily focused on:

- Modeling of tonal and broadband noise generated by the rotating propeller.
- Modeling of underwater radiated noise due to ship hull vibration.
- Standards of underwater noise measurement during sea trials.
- Monitoring and mitigation of underwater noise levels during operations.
- In situ underwater noise measurement campaigns to support standards and policy development;
- Propeller-hull co-design process to achieve lower radiated noise levels in addition to higher energy efficiency.

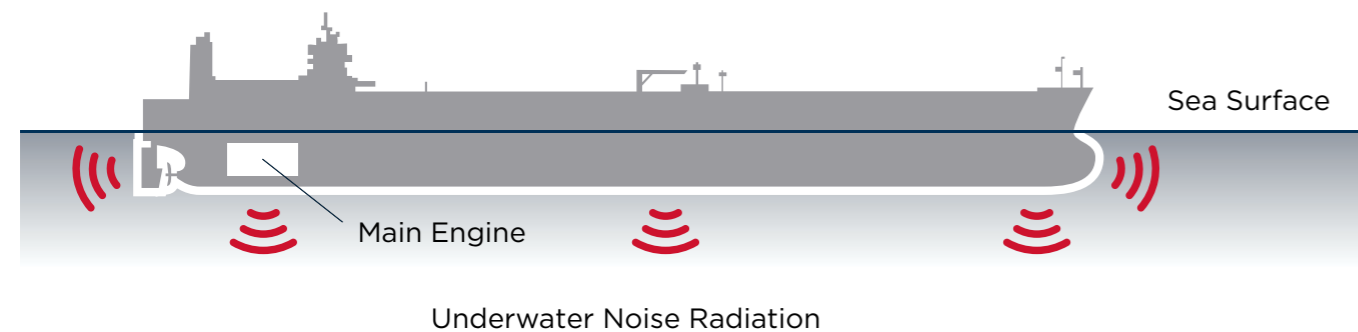
To establish a consistent metric for the underwater noise emitted from commercial ships, significant efforts have been made to develop standards for underwater noise measurement, including ISO 17208 and ANSI/ASA S12.64. Due consideration is given to the effect of site selection, environmental conditions, requirements of measurement instrumentation, test procedures, and measurement data analysis and interpretation during sea trials.

Additional requirements are provided in classification society rules, and the further development of ISO standards specifically for sea trial measurements in shallow water is currently underway.

Compliance with classification society requirements for underwater noise is currently verified through dedicated sea trials. Analysis methods and tools for the prediction of underwater radiated noise can assist in evaluating the noise reduction solutions at the design stage.

The underwater radiated noise analysis typically requires detailed modeling of propeller behavior as well as the hull and machinery configurations. Active research and development have in recent years improved the accuracy of analysis tools capable of modeling the broadband noise and tonal noise emitted from a rotating propeller.

Simplified methods suitable for fast comparative evaluation of potential design solutions at the early design stage are also available and are under continuous improvement. With an increasing market demand for reliable analysis of underwater radiated noise as well as the accumulation of in situ measurement data for validation, the development of the analysis methods and tools has been greatly accelerated.



DESIGN MITIGATION

Typical mitigation measures for different noise sources include:

- Propeller design to reduce propeller cavitation and increase cavitation inception speed.
- Machinery treatment to lower the machinery vibration source level and reduce the vibration energy transferred to the hull structures.
- Hull treatment to improve the ship's hydrodynamic performance and reduce underwater noise radiation efficiency of the hull.
- Technology to reduce propulsion power requirement.

These methods vary greatly in terms of cost, effectiveness, and impact on vessel construction and operation. In general, it is desirable to understand the underwater noise budget and perform a detailed underwater noise assessment and choose the most appropriate solutions to meet the noise limit during the design stage. Fixing underwater noise issues after construction could be difficult and expensive. Close collaborations between shipyard, designers, owners, and vendors are needed to develop an optimized noise reduction plan to meet the noise limit target.

PROPELLER TREATMENT

Underwater noise generated by propellers is mainly caused by certain types of cavitation, such as tip vortex cavitation, blade sheet cavitation, and hub vortex cavitation. Under some conditions, the propeller creates a pressure field on the blade with a region below the vapor pressure of seawater – causing a seawater phase change. As the water vapor enters a favorable pressure gradient, the vapor pocket collapses back into a fluid creating noise. To lower propeller-radiated noise, cavitation needs to be reduced. This can be achieved by enhancing the propeller design or improving the inflow to the propeller by wake optimization. In addition, propeller polishing can remove marine fouling, repair erosions, and reduce surface roughness, which helps to reduce cavitation.

PROPELLER DESIGN

HIGH SKEWED PROPELLER

Increasing the skewness enables the propeller blade to pass through varying wake field much more gradually and improves the cavitation pattern on the blades. The load reduction on the propeller tip also increases the cavitation inception speed. As a result, the propeller-induced vibration and fluctuating noise are reduced. Skewed propellers are usually used in high-powered commercial vessels where propeller-induced vibration may pose a problem. Highly skewed propellers are usually used in warships. The cost for a typical skewed propeller is comparable to that of a conventional propeller. For a highly skewed propeller, the cost may be 10-15% over a conventional one [1] [2].

FORWARD-SKEW PROPELLERS

The load per unit change of incidence to the blade-region of a forward-skew propeller is lower than a straight-edged or backward-skew propeller, which makes it less susceptible to variations in inflow and vessel speed. This enables it to produce less underwater noise. Some findings show that the underwater noise level of a survey vessel could decrease by around 20 dB at 12kHz after replacing the original propeller with a forward-skew propeller. One thing to be paid attention to is that forward-skew propellers are to be installed in tunnels or nozzles to prevent fouling or physical damage to marine life [3].

CONTRACTED AND LOADED TIP PROPELLERS

The contracted and loaded tip (CLT) propeller is designed with an end plate that enables a higher radial load distribution at the blade tip and, as a result, reduces tip vortices and increases the cavitation inception speed. Also, the end plate promotes a higher thrust per propeller area, which can further reduce cavitation and power requirement [4]. According to published reports and studies, the propeller-induced vibration was claimed to be significantly reduced after the CLT propeller was installed [1]. The cost of a typical CLT propeller is about 20% more than a conventional propeller [1].

CONTRA-ROTATING PROPELLERS

The contra-rotating propeller system consists of two coaxial propellers, one rotating clockwise and the other rotating counterclockwise. The aftermost propeller usually has a smaller diameter than the forward propeller so that slipstream contraction effects can be accommodated to recover part of the slipstream rotational energy, which would otherwise be lost. The contra-rotating propeller system increases cavitation inception speed by reducing blade load and blade surface cavitation. It also lowers tip vortex cavitation by optimizing flow circulation [4] [5]. However, this system requires a longer line shafting system and requires additional considerations for the shafting design [6].

KAPPEL PROPELLERS

Kappel propellers modify the propeller tip to reduce tip vortices and increase propeller cavitation speed. The tips are smoothly curved towards the suction side of the blades. It is claimed that Kappel propellers can increase propeller efficiency by approximately 4% [7]. However, other findings suggest that Kappel propellers may not be the best approach to reduce hydro-acoustic noise and require further studies to confirm [1].

PODDED AND AZIMUTHING TRACTOR PROPULSORS

Tractor arrangements of podded and azimuthing propulsors typically have a good flow alignment, an improved inflow velocity field, and a higher cavitation inception speed. This is because they do not have a shafting and A-bracket system ahead of them, causing a disturbance to the inflow, which helps to suppress the blade rate harmonic pressures. However, when used in combinations of two or more, the existence of sets of azimuthing angles should be avoided to prevent large fluctuating forces and moments on the shaft system and significant vibration [5]. Moreover, there is a possibility for these propulsors to radiate higher underwater noise at low frequencies due to the structure-borne noise induced by the electric motors [8].

WATERJET

Waterjet systems use pumps to draw water through an inlet duct, add energy to the water, and expel it at a high velocity. They induce less noise and vibration than conventional propellers. The systems are often used on high-speed vessels or those vessels with shallow draught where conventional propellers do not perform well. For small vessels, when the vessel speed is above 30 knots, waterjets tend to be more efficient than conventional propellers. This could make it an effective noise reduction solution for high-speed small vessels. However, their cost and weight are greater than conventional propellers.

COMPOSITE PROPELLERS

Composite propellers are made of strong and light composite materials. These types of propellers may be significantly lighter, and the propeller blades can be elastically tailored to improve performance. Compared with metallic propellers, composite propellers may offer acoustic and efficiency advantages. Moreover, they are typically corrosive-resistant and have longer fatigue life.

CPP COMBINATOR OPTIMIZATION

Controllable pitch propellers (CPP) can adjust the pitch with different engine speeds to match inflow conditions [3]. AQUO project and SONIC project conclude that if a good strategy is used with a combination of both varying propeller rpm and varying pitch, propeller-induced broadband cavitation noise can be mitigated significantly even at low ship speeds [8]. However, if operating in constant rpm mode, they could generate relatively high underwater noise due to possible high cavitation.

REDUCTION OF TURN PER KNOT (TPK)

Reducing the turn per knot (TPK) of propellers can result in a decrease in the speed of the flow at the blade tips, which can reduce propeller cavitation and increase cavitation inception speed. According to the AQUO project, it may reduce the propeller-induced underwater noise level by one to two decibels (dB) [9]. However, slow propellers generally require a larger diameter. A balance needs to be made between the propeller diameter and TPK.

VOITH SCHNEIDER PROPULSION

Voith Schneider Propulsion (VSP) is widely used on tugs and ferries due to its good maneuverability. It is a device that consists of a circular array of vertical blades rotating around a vertical axis. Each blade can rotate itself around a vertical axis and provide thrust in any direction, which enables it to provide for an almost instantaneous change of direction. VSP produces much less cavitation and lower noise as its rotor does not need to rotate as fast for a given thrust.

WAKE IMPROVEMENT DEVICES

The hull wake flow into the propeller is crucial for propeller performance. A well-regulated hull wake can enhance propulsive efficiency and reduce propeller cavitation, and propeller-radiated underwater noise. There are a variety of wake improvement devices, such as Schneckluth duct, Mewis duct, Grothues spoiler, and stern flap. It is important to ensure that the selected device is suitable for the hull shape, propeller design, and operating profile of the vessel.

SCHNEEKLUTH DUCT

The Schneckluth duct is an oval-shaped duct designed to improve the wake near the upper part of the propeller and reduce blade tip cavitation and fuel consumption. The designer claims that the device can reduce fuel consumption by up to 12% and reduce propeller-induced vibration by up to 50% [10].

MEWIS DUCT

The Mewis duct is a device positioned in front of the propeller along with an integrated fin system. The duct produces a forward thrust by accelerating the hull wake into the propeller. The fin system enhances propeller thrust by providing a pre-swirl to the hull wake and reducing losses in the propeller slipstream. The designer claims that the device can offer an energy reduction of 3 to 8% depending on the individual hull/propeller interaction [11].

GROTHUES SPOILERS

Grothues spoilers are made up of a set of curved fins attached to the hull ahead of the propeller to straighten the flow in front of the propeller, create direct thrust, and improve propeller performance. They can also be applied in combination with the Schneckluth duct. According to the published model test results, Grothues spoilers can offer an energy reduction of 6% to 9% for tankers and bulk carriers in full load and ballast condition, respectively [1].

PRE-SWIRL STATOR

A pre-swirl stator is a device installed on the stern boss in front of the propeller. It optimizes the flow into the propeller to improve overall propulsion performance. It can prevent power loss, reduce propeller cavitation, and increase cavitation inception speed.

PROPELLER BOSS CAP FINS AND PROPELLER CAP TURBINE

Propeller Boss Cap Fins (PBCFs) are small fins attached to the propeller hub. This device can reduce cavitation and save energy by converting hub vortex energy into additional torque and thrust transmitted back to the shaft. According to the experiments conducted by Mitsui OSK Techno-Trade Ltd, PBCF can not only reduce fuel consumption but also reduce propeller-induced noise level by 3 to 6 dB for frequencies above 1,000 Hz [1].

Propeller Cap Turbines (PCT) are similar to PBCFs. They consist of a number of hydrofoil shaped blades integrally cast into the hub cap, which can reduce the hub vortices and decrease fuel consumption [1].

STERN FLAP

Stern flaps are small appendages at the ship transom which can slow down the flow into propellers and create vertical lift force. This can modify the wave resistance, decrease power requirements, improve propeller hull interaction, and therefore reduce underwater noise. According to a study conducted by the U.S Navy, suitably designed and installed stern flaps can reduce the power requirement by about 4 to 19%. Stern flaps have been used on many high-speed small craft, such as workboats, patrol craft, and pleasure craft [12]. The key geometry parameters to be considered during the selection or design of stern flaps are chord length, span across the transom and flap angle.

TWISTED RUDDER

Twisted rudders are designed to avoid rudder cavitation and reduce the loss of rotational energy when the course of the vessel is straight. The twisted shape of the rudder enables it to match the complex incoming flow from the propeller and reduce the angle of attack to the rudder from the swirling flow produced by the propeller [13].

OTHER PROPULSION ENHANCEMENT MEASURES**REGULAR PROPELLER MAINTENANCE**

Imperfections or fouling of the propeller may greatly impair propeller performance. It can increase cavitation and propeller-radiated underwater noise and reduce the propeller efficiency by as much as 2%, depending on the severity of the damage [14]. Regular repair or polishing of the propeller is necessary to ensure that the propeller works in good condition. The maintenance cost depends on the size, complexity, and level of damage to the propeller.

AIR BUBBLE CURTAIN

The air bubble curtain is a system that injects air through holes in propeller blade tips and produces bubbles to isolate the propeller from surrounded sea water. The system is expected to reduce underwater noise by several decibels in medium frequency range [15]. The AQUO project investigated the underwater noise reduction effect of installing an air bubble curtain to both the hull and propeller. It is estimated that a reduction of 3 to 6 dB can be achieved for a generic cargo vessel at 14 knots. However, this system generates additional drag and decreases overall efficiency by 2-3%. This disadvantage could be solved by applying a wake improvement device in conjunction with the air bubble system [8].

MACHINERY TREATMENT

Machinery-induced underwater noise is mainly generated by structure-borne sound. The machinery vibration can first transmit to the foundations and then propagate to the hull structures, resulting in the radiation of underwater noise. Reducing this vibration and isolating the vibration source from the ship's hull are effective ways to mitigate machinery-induced underwater noise.

SELECTION OF QUIET EQUIPMENT

Using quieter machinery equipment is an effective way of reducing vibration energy and underwater radiated noise. However, quieter machines can be more expensive, heavier, or less powerful. For example, gas or steam turbines are, in general, quieter than diesel engines and produce lower vibration levels but with higher cost. High-speed diesel engines are always resilient-mounted and emit lower vibration than low and medium-speed diesel engines but with higher cost and lower fuel efficiency. Diesel-electric propulsion produces less structure-borne noise as the main engine is not directly connected to the propeller by the shaft, but the cost can be much higher. A trade-off should be evaluated at an early stage of design to consider a variety of factors along with underwater noise, such as the operation profile of the vessel, type, and size of the vessel, cost, fuel efficiency, etc. [8] [16].

RESILIENT MOUNT

Installation of resilient mounts can reduce the vibrational energy transferred from the equipment into the ship's structure. There are two types of resilient mounts: resilient, low-frequency isolation mounts and resilient high-frequency isolation. Low-frequency mounts can reduce the structure-borne noise by approximately 20 dB, while the high-frequency mounts can reduce the structure-borne noise by approximately 10 dB [17]. Resilient mounts need to be carefully designed or selected, as unsuitable resilient mounts can worsen the vibration problem. They are unable to reduce the vibration below its natural frequency and may even amplify the vibration in the vicinity of its natural frequency. In addition, the excitation frequencies of the machinery should not coincide with the natural frequencies of the resilient mounts. To avoid such a coincidence, the choice of the resilient mounts should be accompanied with calculations of natural frequencies of a machinery-resilient mount system.

TWO-STAGE ISOLATION

In two-stage isolation systems, machinery equipment is first installed on a heavy, intermediate raft, and then the raft is resiliently mounted to the foundation [4]. In this way, the vibration energy is not directly transmitted to the foundation because there is an extra barrier to the transmission of vibration energy. This method may reduce structure-borne noise transmitted from equipment to ship structure by approximately 20-40 dB [17]. However, the cost of this method is high.

ACOUSTIC ENCLOSURE

Large engine airborne noise produces significant secondary structure-borne noise, which could result in higher ship-radiated underwater noise. An acoustic enclosure is effective in absorbing engine airborne noise. The outer surface of the enclosure is usually made up of a nonporous material, which can greatly reduce airborne noise. The inside of the enclosure is usually lined with an acoustic absorption material to reduce the reverberant sound in the enclosure. To ensure its effectiveness, all penetrations in the enclosure must be well sealed. Also, it should be isolated from the equipment to prevent the transmission of vibration energy from equipment to the wall of the enclosure [17].

ACTIVE VIBRATION CANCELLATION

Active vibration cancellation employs a secondary excitation, such as a shaker, to cancel the original vibration induced by machinery equipment. Sensors are used to monitor the machinery vibration, and the secondary excitation produces a counter phase excitation to offset the machinery vibration excitation. This method is highly effective in reducing vibration at discrete frequencies [4]. The cost of this method is high.

In addition to the machinery treatment solutions described above, there are other methods that can also help to reduce the machinery-induced underwater noise, such as:

- Optimizing the machinery equipment foundation design:
- Improving the foundation design can reduce the amount of underwater-radiated noise induced by the machinery equipment. The improvement can usually be achieved by enhancing the stiffness of the foundation and avoiding resonance of local structures [8] [18].
- Treatment of piping systems:
- Piping systems may produce significant noise and vibration if poorly designed or installed, especially when resonance occurs. Installing hydraulic silencers, flexible hoses, or resilient attachments to the ship structures may help to reduce vibration energy produced by piping systems [18].
- Optimizing the gear design:
- Optimizing the number of teeth and profile shift angle may reduce the vibration energy induced by gear teeth mashing [4].

HULL TREATMENT

Hull treatment solutions can enhance the ship's hydrodynamic performance and therefore improve the wake flow into the propeller and reduce power requirements. Commonly used methods include hull form optimization, installation of hull and propeller appendages such as flow equalizers, and regular cleaning of the hull. Acoustic decoupling coatings and structural damping tiles can also be applied to reduce the radiation efficiency of the hull vibration.

HULL FORM OPTIMIZATION

Hull form has a considerable effect on the hydrodynamic efficiency of the vessel. A good hull form design can provide a more uniform flow into the propeller and reduce propeller-induced noise and vibration caused by uneven wake flow. The noise and fuel consumption reduction potential of hull form optimization is dependent on vessel size, operation profile, and trading areas. Hull form optimization can be achieved by computational fluid dynamic (CFD) assessments and model tests.

REGULAR CLEANING OF THE HULL

Regular hull cleaning and maintenance can improve a vessel's hydrodynamic performance and decrease hull frictional resistance, which, as a result, can improve fuel efficiency and reduce underwater noise. According to AQUO project study results, a 1 to 2 dB reduction may be achieved if the maintenance could improve service speeds by 5%. Hull cleaning is usually performed by a diver or by a remotely operated vehicle (ROV). Fouling condition monitoring systems are increasingly popular, suggesting optimum intervals for hull cleaning [19].

DECOUPLING COATING

Decoupling hull coating is effective to lower the sound radiation efficiency and thus reduce the radiated underwater noise. It is efficient for vessels where machinery noise dominates over propeller noise. Decoupling coatings are usually made up of a low acoustic impedance layer such as rubber foam or visco-elastic tiles. According to the AQUO project study results, this method can reduce the hull radiated underwater noise by around 10 dB at medium frequencies and 20 dB at high frequencies [8].

DAMPING

Applying damping on the hull can reduce the structure-borne noise and reduce the hull-radiated underwater noise. Damping mitigation measures may reduce plate vibration levels by approximately 3 to 10 dB [18]. There are two main types of damping applied in the marine industry: unconstrained layer damping, and constrained layer damping. Constrained layer damping is more effective than the unconstrained one because there is less shearing of the damping layer [18]. The performance of most damping treatments is also highly dependent on damping layer thickness and temperature. Typically, the thicker the damping layer relative to the base plate, the greater the effectiveness. Higher temperatures could reduce the effectiveness of the damping material.

Other hull treatment solutions can also help reduce underwater radiated noise, such as:

- Asymmetric design of the aft body
- This approach is mainly used to improve the wake flow into the propeller of a single screw merchant ship. Model and full-scale tests show that it can reduce power requirements by 5 to 10% [20].
- Double hull design
- Double hull designs can decouple the foundation structure from the outer hull plate, which can reduce the structure-borne sound transmission from the machinery foundations to the outer hull plate [8].

EMERGING TECHNOLOGIES

There are emerging technologies that can replace some of the required propulsion power and potentially reduce underwater radiated noise. Examples include air-lubrication technology, kite sails, flettner rotors, and shore power. Currently, these emerging technologies are under various stages of concept development and pilot operations [4] [21] [22] [23].

OPERATIONAL MEASURES

In addition to appropriate ship design and maintenance, focusing on those major noise contributors, operational measures can also play a big role in reducing underwater radiated noise. Several classification societies offer optional class notations recognizing the operational measures taken by those ships whose trading routes pass through environmentally sensitive areas where underwater radiated noise needs to be controlled within a given limit.

One commonly applied operational mitigation measure is to reduce or eliminate propeller cavitation by reducing speed for ships equipped with fixed pitch propellers. Onboard cavitation monitoring methods have been developed in recent years to assist in detecting the occurrence and strength of propeller cavitation and provide input for adjusting the operational condition. For ships with controllable pitch propellers, reducing ship speed may not be effective in reducing propeller cavitation unless the pitch controller is specifically designed for controlling noise emissions.

CONCLUDING REMARKS

In addition to technical viability and cost considerations, an important backdrop amid growing interest in quieter ships is the maritime industry's quest for decarbonization with challenging goals of achieving the IMO's greenhouse gas (GHG) emission reduction targets. Underwater radiated noise mitigation measures should, therefore, be implemented in such a way that they do not undermine energy efficiency.

Efforts are being made to improve understanding of the impact of various underwater noise mitigation measures on ship energy efficiency and to explore potential co-benefits or trade-offs. The current findings are encouraging in that various measures such as improving propulsion efficiency and reducing ship speed can, in general, reduce fuel consumption and underwater radiated noise at the same time.

Clearly, there is an emerging demand to build quieter commercial ships with lower underwater radiated noise emissions -- a trend that aligns with the overall goal of developing a more sustainable global maritime industry.

In addition to IMO/EU regulatory developments, some local port authorities in environmentally sensitive areas, albeit a small number at present, have started providing port fee reductions for ships equipped with underwater noise reduction measures.

The recognition of the importance of the issue also led to a recent call for revisiting the 2014 IMO Guideline for the reduction of underwater noise from commercial shipping (MEPC.1/Circ.833). The proposal in MEPC 75/14 submitted to IMO in 2020 recommends the review of the IMO Guideline through identifying barriers for its implementation, promoting the development of technological innovations, leveraging synergies with energy efficiency requirements, and developing action plans.

ABS SUPPORT

ABS actively supports the maritime industry's efforts to address the rising demand for quieter ships by providing classification notations and criteria to signify the application of underwater noise mitigation measures through the *ABS Guide for the Classification Notation Underwater Noise*.

For example, vessels entering the Canadian ports of Vancouver and Prince Rupert with the ABS UWN notation are now eligible to receive a reduction in fees. Further efforts to develop more capable tools and techniques to better predict and mitigate underwater radiated noise from commercial ships are currently underway.

ABS UNDERWATER RADIATED NOISE PUBLICATIONS

- *ABS Guide for the Classification Notation Underwater Noise* (April 2020): This Guide outlines the requirements and process to obtain underwater noise notation.



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