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Review

Underwater radiated noise from marine vessels: A review of noise reduction methods and technology

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ABSTRACT

Marine anthropogenic noise has increased significantly over the past few decades, and a growing body of research is highlighting the negative impacts this is having on marine eco-systems. With increasing pressure to reduce the noise generated by commercial and other shipping, there is a need to develop new technologies and look at how existing technology can be applied to reducing vessel noise. In this review, the sources of underwater noise from marine vessels are outlined and a range of devices and technologies are assessed to see how they can be applied to reducing it. Covering cavitation, propeller and flow noise, and machinery noise, a wide range of technologies are reviewed with differing levels of maturity. It is found that there already exists a wide range of technologies that could be readily applied to many vessels, and there are others in earlier stages of development that could provide substantial benefits in the medium-term. However, there is still a lack of quantitative data on the effectiveness of many noise-reducing technologies, particularly at full-scale. This makes legislation more difficult to enact and, together with the lack of economic incentives, is limiting the adoption of such technology by the marine industry.

1. Introduction

Underwater Radiated Noise (URN) from shipping has grown significantly over the past few decades due to increases in both the size and number of commercial vessels. In the past, URN has primarily been a concern for naval vessels, particularly those engaged in anti-submarine warfare or mine counter-measure vessels, and also some research vessels. However, as the detrimental impacts on marine life become clearer, there is a need to understand and reduce the noise produced by commercial and recreational vessels as well. While marine anthropogenic noise has long been recognised as a problem to marine life, early work focussed on the problems of high-intensity, short duration sounds such as those from sonars or pile driving, and much research has gone into understanding the impact of this on marine life (Weilgart, 2007). There is now an extensive body of research clearly showing the negative impacts that anthropogenic noise is having on marine life. This research has accelerated in recent years alongside calls to impose limits on the noise from human activity in the oceans (Williams et al., 2015). Commercial shipping is a major contributor to the rising levels of noise in the oceans, particularly at low frequencies (Hildebrand, 2009), and this has been found to have a detrimental impact on a wide range of marine life including mammals (Richardson et al., 1995; Nowacek et al., 2007), fish (Simpson et al., 2016; Mickle and Higgs, 2018) and invertebrates (Wale et al., 2013; Murchy et al., 2019). These studies highlight the urgent need to reduce noise from shipping to prevent further damage to marine life.

This is now widely recognised, as noted by Simmonds et al. (2014), but only limited action has been taken to-date. It is also recognised that in the absence of a concerted effort by governments, regulators, and shipbuilders, shipping noise is expected to increase in the coming decades (Kaplan and Solomon, 2016). As well as large commercial vessels, the role of smaller vessels and ferries is being increasingly scrutinised, with studies finding that the noise from smaller recreational vessels and ferries can dominate the soundscape in shallow coastal waters (Hermannsen et al., 2019; Cope et al., 2021).

As a result, a wide range of policy options are being proposed and considered for reducing commercial shipping noise (Markus and Sánchez, 2018; Merchant, 2019; Vakili et al., 2020). Changes to vessel routing, speed limits, and changes to vessel design are all being assessed and reviewed at national and international levels. Chou et al. (2021) compile a wealth of reports, journal publications and other documents from governments, inter-governmental bodies, and academic and research institutions related to underwater noise and its mitigation. It is highlighted here that underwater noise from marine vessels is not regulated appropriately at present, but that proper regulation combined

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with better technology could have a significant positive impact on the environment. There are several important international guidelines that support the reduction in underwater noise from shipping. The "EU Marine Strategic Framework Directive 2008/56/EC" of 2008 requires Member States to achieve a "good environmental status" including the reduction of URN, although the practical implications of this are not clear. Additionally, in 2014 the International Maritime Organisation (IMO) published MEPC.1/Circ.833 "Guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life". This document provides some guidance and good practice but does not propose any hard limits or regulations. Despite efforts to classify underwater radiated noise as a form of pollution, it is yet to be formally outlined in the IMO's International Convention for the Prevention of Pollution from Ships (MARPOL). Since 2019 there has been a call from a number of member states to revisit the IMO guidelines for underwater radiated noise. This was initiated in January 2019, where a technical workshop brought together over 140 participants from around the world. The workshop pulled together best practice from industry and outlined mitigation techniques in the VARD report (Vard, 2019). The work from the event contributed to several papers submitted to IMO's Marine Environment Protection Committee (MEPC) in the following years. Following MEPC76 in June 2021, the IMO formally accepted the proposal from Australia, Canada, and the United States to review the 2014 guidelines and work is now underway to update them.

The lack of overarching international regulation has not prevented some local schemes from being developed. Vessels entering the Canadian ports of Vancouver and Prince Rupert are eligible for reduced harbour fees if they meet certain noise and pollution criteria. Whilst schemes such as this are not widely implemented at the time of writing, many other governments and ports are reviewing their local environments. This includes creating underwater soundscapes to develop a clearer understanding of the local acoustic environment, such as that conducted at the Port of Gothenburg (Lalander et al., 2021).

The internal noise and vibration within a ship is highly regulated due to their health and safety implications, and so standardised definitions and measurement procedures exist for this. The standardisation of external radiated noise is, on the other hand, far less developed. The main areas of standardisation so far have been focused on the consistent measurement of underwater noise including ISO 17208 "Underwater acoustics — Quantities and procedures for description and measurement of underwater sound from ships" and ANSI/ASA S12.64 "Standard Quantities and Procedures for Description and Measurement of Underwater Sound from Ships". An important area of future development is the standardisation of URN measurement in shallow water. Measurements in shallow water are difficult to perform because of the complex interactions between the acoustic waves and the seabed and sea surface. Work is ongoing to develop a Section 3 of the existing ISO 17208 standard to look at shallow water measurements (Ainslie et al., 2021).

One of the main challenges to bringing in regulations such as mandatory noise limits is the lack of data. Regulations analogous to the Energy-Efficiency Design Index (EEDI) are often discussed, but this would require a much better understanding of the noise levels produced by both new and in-service ships. Acoustic trials are not common and seldom carried out for commercial vessels, meaning we have only a limited idea of how much noise most vessels actually produce. A number of research programs have sought to address this issue, including the EU-funded AQUO project, Hallander et al. (2015) and Audoly et al. (2015). This work has given rise to parametric models for the level of noise produced by a given ship, but further data is needed to improve and test these models across a broader range of vessels. There is also significant uncertainty in the efficiency and cost effectiveness of the mitigation measures as well as a lack of a harmonised and standardised methodology for underwater radiation noise measurement (Vakili et al., 2020).

Most classification societies now offer a *Quiet Ship Notation* to help guide and verify the low signature credentials of a vessel. Certification is normally outlined through 3rd octave target sound pressure levels and tested through the use of full-scale trials, although it is acknowledged that this measurement process is fraught with challenges of consistency and standardisation. Efforts are now being made to compare the different notations across the different class societies and also to harmonise some definitions and procedures (Ainslie et al., 2022). All of the notation targets broadly follow the same pattern for noise reduction linked to scientific research on marine life hearing ranges: the target curves will typically create a line or "V" shape curve between 10 Hz and 1000 Hz (recognising the critical hearing ranges for marine life), before tapering off after 1000 Hz in recognition of higher dissipation rates at higher frequencies. However, it should be noted that some disagreements remain about how to classify vessels and what the exact targets should be for each vessel type.

As well as the design of a vessel and the technologies used, operational conditions and speed are important determining factors for radiated noise levels. Recently, the Vancouver Fraser Port Authority published results of a study where vessels were asked to reduce speed to 11 knots (MacGillivray et al., 2019), with a view to reducing to levels of noise produced. This showed significant reductions in the levels of URN recorded, showing that it could be an effective measure. However, a more recent study has shown that some vessels actually produce more noise at lower speeds (McIntyre et al., 2021). Despite the general trend supporting the idea that slower vessels produce less noise, this study highlights the need to understand the physics of noise generation from different vessels, and the importance of developing better designs and technology to limit the noise produced. The use of speed reduction as a means of reducing noise was also explored by Tani et al. (2015). In this work, two mechanisms used for speed reduction were compared: reducing propeller revolutions per minute (RPM) at constant pitch, and reducing pitch at a constant RPM. The study showed that reducing speed via an RPM reduction was indeed highly effective at reducing the levels of URN, but the same was not true for a pitch-reduction at constant RPM. In fact, reducing the pitch was shown to cause pressure-side cavitation, which in some cases led to an increase in the overall levels of noise. This again highlights the complex relationship between the operating condition of a vessel and the radiated noise levels, particularly when considering the different propulsion architectures used.

URN from a ship arises from multiple sources, leading to a complex signature covering a wide range of frequencies. Descriptions of these sources can be found in many works, for example Abrahamsen (2012). A number of research programs have greatly enhanced our understanding of the make-up of ship radiated noise, including the large collaborative EU projects (SONIC, SILENV, AQUO). Such programs have improved our understanding of cavitation noise, machinery noise, and other components, but they have also highlighted the large differences that occur between vessel types and operating conditions. This provides further weight to the argument that more data is needed across a broader range of ship classes. The signature is often broken down into machinery noise, flow noise, and propeller noise which includes cavitation noise (Rizzuto et al., 2015). There are numerous published works of full-scale trials and other experimental studies that demonstrate the levels of noise produced by different vessels, and these also provide details on some of the dominant components (Arveson and Vendittis, 2000; McKenna et al., 2012; Li et al., 2018). These studies tend to show that low frequency noise (<125 Hz) is dominated by tonal components associated with the main engine firing rates and the propeller blade-rate harmonics. Higher frequency noise is made up of machinery noise, propeller and flow noise, and cavitation, but breaking this down into its constituent components is challenging. This leads to uncertainty as to the relative importance of the different components and further research is needed to better understand this. However, by targeting each of the individual sources, significant reductions in the overall noise produced should be achievable. Furthermore, by considering the sources individually and examining their physical origins, designs and technology can be developed and applied more successfully to reducing the overall radiated noise levels.

This paper provides a review of the sources of underwater radiated noise from marine vessels, together with a wide range of design methods and technologies that might be applied to reduce it. As well as reviewing existing technologies and design techniques, this work also includes an extensive review of new and novel technologies from a range of industries to see how these might be applied to reducing underwater radiated noise. This includes technology and design innovations for reducing propeller cavitation, passive design modifications to reduce leading and trailing edge noise, as well as meta-materials that could be used to reduce acoustic propagation across a range of applications. The technology considered here is drawn from a range of industries and different areas of research, with a view to assessing how they could successfully be applied to reducing URN from marine vessels. Not all the technology considered has been developed for noise reduction, but for efficiency gains or flow control. However, by understanding the underlying physics of how such devices work, their application to reducing particular sources of noise becomes clear. Some of this technology is in its infancy and would require extensive research and development before it could be applied at scale on a ship. However, much of the technology discussed has been shown to be effective by multiple experimental and numerical studies, and some is now being used within industry, although not necessarily on marine vessels. The maturity of each of the technologies and devices as applied to a marine vessel is discussed, together with the research and development needed to progress the maturity of the technology.

Beginning with a review of noise sources from a marine vessel in Section 2, a review of design methods and technologies that can be adopted to reduce noise is presented. Reducing propeller cavitation, non-cavitating propeller noise, and flow noise is considered in Section 3, and reducing machinery noise is considered in Section 4. Conclusions are presented in Section 5, along with recommendations for future work, with a particular focus on the research and development needed to increase the technology readiness levels of the technologies discussed.

2. Source of URN from marine vessels

The total URN of a vessel is often split up into machinery noise, propeller and flow noise, and cavitation (see Fig. 1). The contribution of each component will differ from one vessel to the next and is also strongly dependent on the vessel's speed. Studies have shown that the signature tends to be dominated by machinery noise at low speed, with cavitation becoming the dominant source at higher speeds (Moreno et al., 2015).

Machinery noise contributes to the URN of a vessel by inducing vibration of the hull plating and by transmitting sound through openings that are directly connected to the sea. There are multiple paths by which the sound and vibration from machinery radiates into the surrounding water. The first of these is where vibrations transmit through the machinery mounts into the hull structure and then into the shell plating. The airborne transmission of sound from the machinery inside the ship also induces vibrations of the structure, which transmits to the shell plating. A description of this can be found in Spence and Fischer (2016). Low speed diesel engines produce low frequency tonal noise associated with the engine firing rates and this can be readily identified during acoustic trials, see Arveson and Vendittis (2000) for example. Other machinery including generators, pumps, and heating, ventilation, and air conditioning (HVAC) systems will all contribute to the overall sound radiated into the surrounding water. The level of radiated noise resulting from onboard machinery is therefore very specific to the type and size of the vessel, as well as the mounts used for individual engines, generators, etc.

Propeller noise is often split into cavitating and non-cavitating, with cavitation noise tending to dominate at higher speeds (Salinas and Moreno, 2014). For a non-cavitating propeller, studies have shown that tip vortex noise is the dominant source if the propeller is operating in a uniform flow (Ianniello et al., 2013; Keller et al., 2018). Propellers also produce trailing edge and leading edge noise, as well as noise from the hub. Trailing edge noise results from the turbulent boundary layer convecting over the trailing edge, where the fluctuations scatter as acoustic waves. This can be broadband or narrowband, depending on factors such as the Reynolds number and the thickness of the boundary layer relative to the edge thickness. This can also lead to propeller singing, where a fluid–structure interaction leads to a high-pitched tonal sound being produced. This occurs due to a matching of the dominant vortex shedding frequency and the natural frequency of the blade, and details of the physical mechanisms of this can be found in Blake (2017) and Fischer (2008). A detailed explanation of trailing edge noise together with a range of experimental data and numerical methods can be found in Blake (2017) and Brooks et al. (1989). Leading edge noise results from unsteady and turbulent flow interacting with the leading edge of a lifting surface, which induces pressure fluctuations and hence noise.

Low frequency tonal noise occurs as a result of the propeller rotating through a spatially-varying wake field which can lead to cavitation as well as non-cavitating noise. A typical wake is shown in Fig. 2 together with the axial velocity at a non-dimensional radius of $r/R = 0.7$. The variations in the axial velocity cause the local flow velocity and angle of attack to vary as the blades rotate, leading to a fluctuating pressure field. This induces dipole-type noise and, if cavitation is present, fluctuating cavity volumes on the surface of the blades.

At higher speeds, propeller cavitation is one of the main sources of URN and research into reducing it has been ongoing for many decades. For commercial vessels, the cavitation inception speed can be as low as 8 knots (Leaper et al., 2014) and so it is likely that most commercial vessels will experience cavitation. Cavitation noise is complex and arises in many different forms depending on the propeller and hull design, as well as the operating conditions. Low frequency cavitation noise tends to be due to attached cavitation bubbles oscillating as the propeller rotates through a spatially varying wake field, whereas detached cavitation and vortex cavitation tend to increase noise levels at higher frequencies. Vortex cavitation can occur at the tip and the hub. Tip vortex cavitation is often the first to occur and arises due to the low pressure in the tip vortex core. This type of cavitation is very sensitive to the particular dynamics of the tip flow and also the water quality, which refers to the size and distribution of nuclei in the water (Arndt et al., 1991; Chen et al., 2019). Therefore, both propeller design and operating conditions are important determining factors here. Hub vortex cavitation occurs when the pressure in the hub vortex drops below a certain point, which is again dependent on the water quality as well as the dynamics of the vortex itself.

Sheet and bubble cavitation can occur when the pressure drops below the cavitation inception point at, or close to, the propeller blade. This will typically occur on the suction side, but can also occur on the pressure side in off-design conditions or for controllable-pitch propellers operating at reduced pitch. Bubble cavities originate at the blades but travel with the flow, and have historically been associated with high noise levels and erosion. However, research in the 1990s showed that, at full-scale, bubble cavitation was likely less of an issue than previously thought, and it was suggested that sheet and cloud cavitation should be given more attention (Kuiper, 1998). Unstable sheet cavitation leads to cloud cavitation, which tends to lead to a large increase in the radiated noise levels. The stability of sheet cavitation and the dynamics that lead to cloud cavitation have been studied in many works, see Pham et al. (1999) for example. Sheet cavitation is found to increase the noise levels at blade rate harmonics and also at higher frequencies, where the increase in broadband noise is due to splitting and collapse of bubbles (Salinas and Moreno, 2014). Noise is

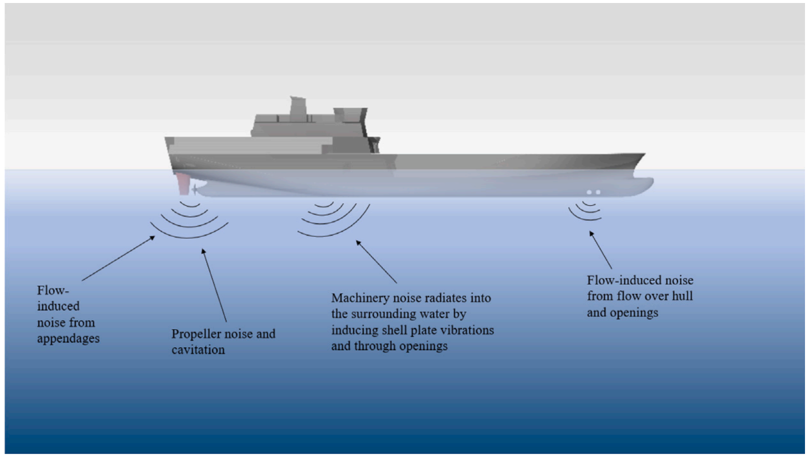
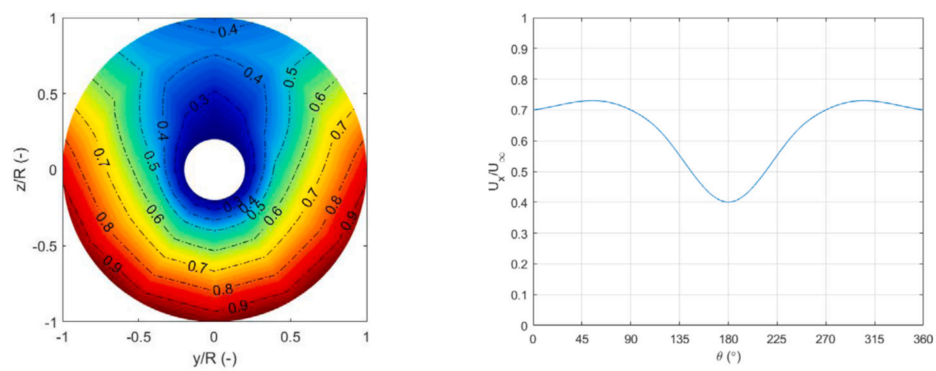


Fig. 1. Sources of underwater radiated noise from a typical marine vessel.



(a) (b)

Fig. 2. A typical nominal wake field for a single-screw vessel: (a) shows the non-dimensional axial velocity U_x/U_∞ and (b) shows the non-dimensional axial velocity at a radius of $r/R = 0.7$, where $\theta = 180°$ denotes top-dead-centre.

produced by growth, oscillation and collapse of cavitation bubbles, as well as by splitting and coalescence. It has been shown that cavitation bubble collapse can produce noise several orders of magnitude higher than the noise associated with growth, oscillation, splitting (Choi and Ceccio, 2007). More detailed expositions of the physics and types of cavitation, as well as cavitation noise can be found in Arndt (2002), Franc and Michel (2006), Foeth et al. (2008) and Blake (2017).

As well as noise from the propeller, the flow over the hull and appendages will also produce noise, and this generally becomes more prominent at higher speeds. Both leading and trailing edge noise will be produced by appendages such as the rudder, A-brackets and stabiliser fins. Interaction noise will also be important here. This arises when turbulence from the flow over one structure interacts with another. For example, the unsteady turbulent flow from a propeller will interact with the rudder, inducing pressure fluctuations on the rudder surface. Hydrofoils will produce trailing edge noise, tip vortex noise, and may also cavitate. The dynamics of hydrofoil cavitation are discussed in a great many works, for example Blake et al. (1977), Huang et al. (2013) and Blake (2017).

Noise from openings arises primarily from two sources: pumps used within systems directly connected to the sea, and from the flow over the openings and sea chests. Noise and vibration induced by flow over sea chests has been noted as a problem on several vessels (Carlton and Vlasic, 2005), and is most likely to affect those operating at higher speeds. Lateral thrusters may also be categorised in this way, with the thruster producing noise when in operation as well as noise from the flow over the opening. The issue of lateral thruster noise has received more attention recently, both due to onboard noise and URN (Reinikainen, 2021).

3. Reducing propeller cavitation and non-cavitating propeller noise

In this section, technologies and design methods for reducing propeller cavitation, non-cavitating propeller noise, and flow noise are considered. The origins of many sources of non-cavitating propeller noise share much in common with the cavitating sources, and so similar technologies, devices and design methods are often used to reduce both. For example, devices that reduce the onset of tip vortex cavitation do so by reducing the vortex strength, which should also reduce the noise produced by the non-cavitating vortex. Similarly, devices that improve wake uniformity will potentially reduce sheet cavitation (if present) as well as the non-cavitating component of the blade-rate noise.

3.1. Sheet, bubble, and cloud cavitation

Whilst sheet, bubble, and cloud cavitation are different phenomena, there are commonalities in their origins and so it is helpful to consider them together when reviewing designs and technology for reducing their presence. Efforts to reduce these types of cavitation have focussed on the propeller blade area ratio and the section design. Increasing the blade area ratio allows for the propeller blades to have a reduced load per unit area while maintaining the overall thrust. This, in turn, results in a higher minimum pressure on the suction side, thus reducing the propensity for cavitation. This has been understood for many years, following studies by Burrill and Emerson (1963) and others.

For section design, it is preferable from a cavitation perspective to design sections that have a more even pressure distribution along the chord length, such as a round-back section. Wing section profiles such as the NACA 4-digit series have a very favourable lift-to-drag ratio, but they also have a very uneven pressure distribution, with most of the lift being generated shortly downstream of the leading edge. By designing sections with a more even pressure distribution, it is possible to generate the same amount of lift along the chord length but have a higher minimum pressure, which can alleviate or at least reduce the levels of cavitation for a given speed. This is now common design practice for modern propellers. The development of sections with improved cavitation performance can be found in a number of works, for example Dang (2004) and Zeng and Kuiper (2012), and this has been effective at increasing the cavitation inception speed for many vessels.

As well as the propeller design, one should also consider the local flow field that the propeller is operating in, as this can have a large influence on the presence and dynamics of cavitation. As discussed in Section 2, the spatial variations in the nominal wake field lead to pressure fluctuations on the propeller blades, which in turn can lead to oscillating cavity volumes. Therefore, improving the level of wake uniformity will reduce the magnitude of these oscillations, and potentially delay the onset of this type of cavitation. The design of the hullform is crucial here, and efforts should be made from an early stage in the design to ensure as uniform a flow field as possible in the propeller plane. Improving wake uniformity can also improve propulsive efficiency, and a wealth of research has gone into this over the past 20 years. One such device that can improve the wake uniformity is the vortex generator. These devices have been applied widely for controlling boundary layer separation (Lin, 2002), reducing vortex-induced vibration (Xin et al., 2018), and also improving the uniformity of the flow into a ship propeller (Kim et al., 2015). Depending on the application, vortex generators can be used to promote local mixing, prevent separation, or to re-structure the flow field (Jirasek, 2005).

Applied to flow control at the stern of a ship, vortex generators can be used to transfer momentum towards the top of the propeller plane, increasing the axial velocity and reducing flow separation. This was demonstrated by Li et al. (2021), who showed that placing a vortex generator on the hull upstream of the propeller reduced flow separation at the top-dead-centre location, which led to a decrease in the amplitude of the pressure fluctuations at the blade-rate harmonics. Combined with a high-skew propeller, see Ji et al. (2014) for example, such technology has the potential to dramatically reduce low frequency propeller noise as well as cavitation. As well as being a mature technology within the aerospace industry, vortex generators have now been successfully trialled on full-scale ships, indicating a high level of maturity. Saydam et al. (2018) used CFD to design vortex generators which were then retro-fitted to a tanker (see Fig. 3). Analysis carried out on the tanker indicated a significant reduction in vibration at the blade-rate harmonics, indicating that the vortex generators were successful in improving the wake uniformity on a full-scale ship.

Fig. 3. Vortex generators fitted upstream of a propeller on a tanker.
Source: Reproduced from Saydam et al. (2018).

3.2. Tip vortex cavitation

Tip vortex cavitation (TVC) has received much attention as it is often the first type of cavitation to appear on a modern propeller. This is due to improved propeller section design over past decades which has led to the inception of sheet cavitation being delayed, and it is now more common for tip vortex cavitation to appear first (Kuiper et al., 2006; van Terwisga et al., 2007). As a result, extensive research has gone into understanding, predicting, and suppressing tip vortex cavitation. Common design methods to delay the onset of tip vortex cavitation are often based on tip off-loading (Molland et al., 2017; Park et al., 2014), which reduces the pressure differential between the two sides of the propeller close to the tip, thus reducing the tip vortex strength. This tends to reduce the efficiency of the propeller, as the lift-to-drag ratio of the propeller surface close to the tip is decreased. Novel propeller designs, such as the contracted and loaded tip (CLT) propeller (Gaggero et al., 2016) have been shown to reduce the presence of tip vortex cavitation and these have now been installed on a range of vessels (Ebrahimi et al., 2019).

A number of active and passive techniques have also been proposed, either for suppressing TVC or reducing the noise produced. One such active method is to inject either water or a polymer solution into the vortex core, which increases the core radius and hence increases the pressure in the vortex core (Chang et al., 2011; Park et al., 2014). The use of polymer injection for foils and propellers was first used in an attempt to reduce drag (Brennen, 1970) but it was subsequently found that it might be successful in delaying the onset of TVC. Chahine et al. (1993) showed that injecting a polymer solution at the tip delayed the onset of cavitation compared to injecting water although a more recent study by Lee et al. (2018) showed that water injection could be effective. Studies have shown that injection of polymer solutions and dilute solutions can both suppress tip vortex cavitation, but that the mechanisms are different for the two cases. In one such study (Fruman and Aflalo, 1989), it was found that a homogeneous polymer solution inhibited TVC by reducing the pressure differential on the two sides of a foil, thus reducing the circulation at the tip. Injection of a dilute solution led to a much smaller change in the lift, but altered the tangential velocity field in the core, which led to a delay in cavitation inception.

An alternative but related method is to attach a flexible fibre to the tip which is drawn into the vortex core. Studies on water and polymer injection have found that the results are highly dependent on the location of the injection port. This leads to issues around repeatability and potentially limits the conditions under which the technique would be effective. Park et al. (2014) instead propose attaching a flexible thread to the tip of the propeller blades, which is sucked into the vortex core. This was found to be effective in suppressing TVC and may be a more robust approach than water or polymer injection. Fig. 4 shows how effective this can be, with the thread completely suppressing the tip vortex cavitation in certain conditions. This idea is further investigated by Amini et al. (2019b). Here, a flexible thread is shown to be most effective in suppressing TVC when its diameter is similar to that of the viscous vortex core. The thread is periodically pulled into the vortex core where it oscillates, thickening the vortex core and suppressing the cavitation. These studies also suggest a negligible impact of the thread on the propeller efficiency.

Whilst these techniques have been shown to be effective in laboratory experiments, they are not yet used on full-scale vessels and further research is needed to demonstrate their effectiveness in realistic environments. One of the main appeals of using a thread instead of injection of water or a polymer into the flow is the ease of implementation on a full-scale vessel. Active methods such as fluid injection increase cost and complexity, and this may limit their feasibility compared to a more passive technology such as a flexible thread. Furthermore, depending

Fig. 4. Images of tip vortex cavitation from a propeller blade without thread (left) and with a flexible thread (right).
Source: Reproduced from Park et al. (2014).

on the particular molecular structures used, injection of a polymer may be detrimental to the environment.

As well as active methods, passive methods have also been developed for reducing or suppressing TVC. It has been shown both experimentally and numerically that surface roughness can be used to suppress TVC (Asnaghi et al., 2020; Svennberg et al., 2020; Krüger et al., 2016). These studies showed that roughness modifies the vortex roll-up process leading to a weaker vortex forming, with a higher core pressure than is observed for a smooth blade. Clearly, there is a trade-off here between vortex suppression and the efficiency of the propeller which is degraded by the presence of surface roughness. Asnaghi et al. (2021) found that by positioning the roughness only at the tip and a small area on the leading edge, TVC mitigation was achieved with a modest 1.8% reduction in propeller efficiency.

One measure that has its origins in aerospace engineering is the use of winglets to reduce the vortex strength. The addition of winglets to aircraft wings for reducing trailing vortices has been widely research, for example Lee and Su (2012) and Lee and Choi (2015). Recent studies have shown that such technology can be successfully applied to marine propellers (Amini et al., 2019a; Gao et al., 2019). Designed appropriately, the winglets have been shown to decease the core axial velocity and increase the core radius, thus increasing the core pressure and preventing, or at least delaying TVC. However, the winglets are likely to generate their own noise and further research is needed to understand how they would affect the overall sound pressure level at different operating points. There are clear similarities in the mechanisms these different techniques invoke. In particular, winglets, the injection of water or polymer solutions, and the use of flexible threads all act, at least in part, to increase the vortex core diameter and so increase the pressure.

An alternative approach is to place holes in the propeller tip to reduce the pressure differential on the two sides. Using both experimental and numerical methods, Aktas et al. (2020) showed that locating holes in specific places close to tip modified the nature of the cavitation and reduced the overall sound pressure level but with a loss of efficiency of 2%. One potential issue with technology of this nature comes from the environment in which it operates. Propellers are susceptible to the build-up of marine fouling, and this can occur quite rapidly. It is quite probable that this will block the pores used to alleviate the tip pressure differential and reduce the effectiveness of this over time. Further research could examine this to better understand the viability of this technology and also try to develop mitigation measures to ensure its continued effectiveness.

3.3. Hub vortex cavitation

Whilst not as large a contributor to the overall sound level as cloud or bubble cavitation, hub vortex cavitation may still be important, particularly if other forms of cavitation are not present. It is therefore worth exploring technologies that can reduce hub vortex strength and potentially suppress hub vortex cavitation.

Energy-saving devices have been developed that may also act to suppress, or at least reduce hub vortex cavitation and associated noise. Propeller boss-cap fins have been shown to be an effective energy-saving device that work by recovering energy from the hub vortex. This, in turn, reduces the strength of the vortex, which will reduce associated noise and help to reduce or remove hub vortex cavitation. These are a mature technology and have been applied to many in-service vessels (Ouchi et al., 1989; Hansen et al., 2011). The effect of a boss cap fin on hub vortex cavitation can be seen in Fig. 5, reproduced from Sun et al. (2016). This shows a propeller in a cavitation tunnel with and without a boss cap fin, showing the complete removal of the hub vortex cavitation. A wealth of literature is available on these devices, with both numerical and experimental methods being successfully used to design and optimise them (Kawamura et al., 2012; Seo et al., 2016; Mizzi et al., 2017). However, only a few studies quantitatively consider the impact of removing hub vortex cavitation on noise and so further research is needed to understand the overall impact. Tachikawa et al. (2019) do consider this, and find that removing hub vortex cavitation reduces the overall sound pressure level by 6 dB alongside a modest improvement in efficiency for the case considered. Several other devices have been developed to remove the hub vortex, often by integrating the propeller boss into the rudder (Okada et al., 2015; Su et al., 2020). Again, these devices have been developed for energy-efficiency, but it would be of interest to see if these devices can have an appreciable impact on the noise levels.

It should be noted that the noise associated with hub vortex cavitation is likely to be substantially less than that produced by cloud or bubble cavitation, if present. In this case, the effectiveness of removing the hub vortex cavitation on the overall noise levels is likely to be minimal. However, if other measures have been taken to limit these forms of cavitation, then eliminating a cavitating hub vortex is an important step to further reducing the overall noise levels.

3.4. Noise reduction through reduced propeller loading

In general, the more heavily loaded a propeller is, the more noise it will produce. A heavily loaded propeller is associated with lower pressure on the back of the blade, which increases the levels of cavitation. Higher propeller loading will also lead to a higher pressure differential between the pressure and suction sides, which increases the strength of the tip vortex. Dipole-type noise, which results from pressure fluctuations on the blades, scales according to $p_a \propto U_r^6$, where p_a denotes the acoustic pressure and U_r is the resolved velocity in the co-ordinate system of the propeller blade section. Therefore, all else equal, a propeller rotating at a higher speed will produce more noise. Reducing the rotation speed of a propeller is seen as a practical means of reducing noise and so energy-saving devices (ESDs) that can provide either additional thrust or improve the propulsive efficiency should be considered as part of this. There is an important caveat here: if the propeller thrust is reduced by way of pitch reduction, as is common practice for a controllable-pitch propeller, then noise reduction may not be realised due to the propeller operating in an off-design condition. Controllable-pitch propellers are susceptible to pressure-side and root

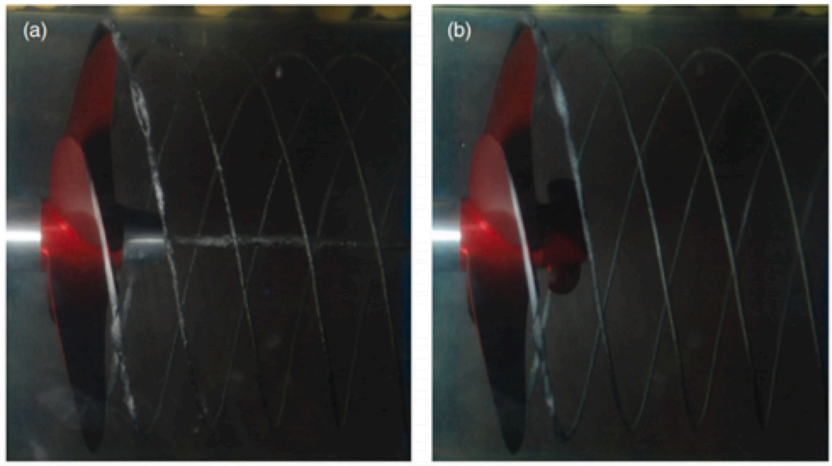


Fig. 5. (a) Propeller without PBCF showing tip and hub vortex cavitation and (b) propeller with PBCF showing no hub vortex cavitation.
Source: Reproduced from Sun et al. (2016).

cavitation when operating at reduced pitch. The importance of this was highlighted by Tani et al. (2015), who found that a speed reduction achieved through a pitch reduction could lead to an increase in the radiated noise levels due to the presence of pressure-side cavitation. Therefore, from a noise perspective, energy-saving devices should be seen as a mechanism to reduce the propeller rotation rate, as this has the most potential to reduce the radiated noise levels.

A wide range of devices have been developed in order to improve the vessel propulsive efficiency. These devices have become more prominent in recent years following the introduction of the Energy Efficiency Design Index, and a wealth of research and development has gone into their design and implementation on a wide range of vessels. Whilst the correlation between energy efficiency and noise reduction is not always as strong as one would like (for example blade tip offloading reduces TVC but at a cost in terms of efficiency), there are Energy Saving Devices that may act to reduce the acoustic signature as well.

Many of the novel devices being developed and applied to commercial vessels, such as Flettner rotors, kites, and turbo-sails (Chen et al., 2010; Traut et al., 2014) provide thrust and so can be used to reduce the loading on the propeller. If this technology is used in conjunction with a reduction in propeller speed, it should reduce the levels of cavitation and hence reduce the noise. The extent to which noise levels will be reduced will depend on the particular vessel and the prevailing operating conditions, but if such devices can reduce the propeller loading such that it ceases cavitating, then substantial benefits may be realised in terms of URN.

Other devices designed to increase propulsive efficiency could also lead to a decrease in the noise produced by the propeller, particularly if the propeller is cavitating. Examples of such technology include pre-swirl stators (Zondervan et al., 2011; Park et al., 2015) and pre-swirl ducts (Shin et al., 2013) which modify the flow field into the propeller in order to improve the efficiency. However, many of these devices will also generate their own noise, and so their suitability as a tool for overall noise reduction should be assessed considering the whole system, not just the impact on the propeller.

3.5. Leading and trailing edge noise

When compared with the noise levels from cloud and bubble cavitation, leading edge and trailing edge noise from propeller blades and other lifting surfaces may not seem like a priority. However, there are instances where such components can be problematic and where efforts should be made to minimise them. Leading and trailing edge noise occur for all lifting bodies operating in turbulent flow. Within the context of a marine vessel, this includes the propeller blades, the rudder, A-brackets, stabiliser fins, as well as rotating machinery on board the ship such as pump impellers and fans in HVAC systems. For vessels that are not experiencing cavitation, either by design or speed, and for those with particularly strict noise requirements such as research or naval vessels, further reductions from fluid-induced can still be achieved by minimising the noise produced by lifting bodies.

One particularly troublesome problem related to the flow over the trailing edge is propeller singing. This can occur when the frequency of the vortex shedding at the trailing edge is close to the resonant frequency of the blade (Park et al., 2005; Fischer, 2008). The phenomenon has been recognised for many decades, and early studies from the 1960s (Van de Voorde, 1960) considered the possible origins and solutions. The most common treatment for this problem is to use an anti-singing edge, which usually takes the form of a bevelled trailing edge. The effectiveness of this has been known for many decades, but the problem of propeller singing still occurs on many vessels, see Bonney and Bahtiarian (2006) and Fischer (2008) for example. As well as a bevelled edge, many of the developments discussed in this section, particularly the use of wavy and serrated edges, may also help to alleviate propeller singing.

Much inspiration for reducing noise from lifting surfaces can be found in the natural world, and a range of bio-mimetic designs have been developed and analysed numerically and experimentally. Designs have been developed to reduce both leading and trailing edge noise, which is produced by propeller blades and appendages on marine vessels. One such area where biologically-inspired designs have been applied is in the suppression of trailing edge instability noise. This occurs at moderate Reynolds numbers and afflicts wind turbines, gliders and other small aerial vehicles as well as some rotating machinery (Yakhina et al., 2015). Marine propellers and appendages typically operate at very high Reynolds numbers, where instability noise is unlikely, but there are important lessons that can be learnt from the research into instability noise. Specifically, one of the conditions required for this type of noise is a strongly span-wise coherent boundary layer where two-dimensional tubular vortices scatter at the trailing edge. Effective measures to reduce instability noise often work by breaking up these structures before they can scatter as acoustic waves. One of the most widely researched technologies for reducing this type of noise is the serrated trailing edge, which helps to break up these structures as they scatter (Jones and Sandberg, 2012; Chong and Joseph, 2013; Hu et al., 2022).

Despite being primarily designed to reduce instability noise, serrated edges can be applied to high Reynolds number marine applications including appendages and propeller blades. In such applications, the boundary layer will be fully turbulent and instability noise is highly unlikely to occur. However, as the Reynolds number increases, the boundary layer thickness reduces relative to the thickness of the trailing edge. Thus, beyond a certain Reynolds number, the edge becomes hydrodynamically blunt, and a narrowband component will re-emerge, associated with coherent shedding. Because serrated edges reduce the coherence of the scattered acoustic waves, they should also be effective here. The use of trailing edge serrations was considered for a turbulent boundary layer by Moreau and Doolan (2013). Here, experimental studies showed that the serrations reduced the noise across a wide range of frequencies but were most effective at the frequency range associated with the vortex shedding due to trailing edge bluntness. The relationship between the size of the serrations relative to the Strouhal number of the vortex shedding was found to be important for maximising the reduction in acoustic intensity.

We can therefore conclude that the physical mechanism by which the serrations reduce noise is similar, irrespective of the flow regime. That is, if designed appropriately, serrated edges act to prevent coherent turbulent structures from scattering as efficiently and so reduce the noise produced. There is likely to be an additional benefit to the use of serrations that can be seen when considering interaction noise. If they are used on an upstream geometry, they will break up the larger turbulent structures into smaller structures where the energy is distributed over a wider range of frequencies. Thus, the turbulent flow that interacts with the downstream geometry will be less coherent with many different scales and phase relationships, leading to less noise being produced. Furthermore, the break-up of larger structures into smaller structures accelerates the process of turbulent decay, as smaller structures are more affected by viscous dissipation.

A recent study used CFD to assess how serrated edges could be applied to a duct to reduce pump-jet noise (Qin et al., 2019). This was partly inspired by research chevron nozzles that have been shown to reduce jet noise for some types of turbofan engines (Callender et al., 2005; Bastos et al., 2017). Jet noise is not prevalent for marine propulsion systems as the velocity gradients are too small, but the study showed that a "sawtooth" duct resulted in a modest noise reduction of between 2.5 and 5 dB compared to a conventional duct. Two mechanisms were identified that led to this reduction. Firstly, the turbulent kinetic energy was found to be lower in the wake for the pump-jet incorporating the sawtooth duct. Secondly, the turbulent structures in the wake were found to be smaller and broke down more rapidly. This second mechanism is the same as that identified from the studies of trailing edge instability noise in that the sawtooth duct acts to break up larger coherent turbulent structures into smaller, less coherent structures.

Serrated edges have also been combined with other modifications. Wang et al. (2017) used large eddy simulations together with a Ffowcs-Willams and Hawkings model to assess the noise reduction from a foil with surface ridges and trailing edge serrations that are based on structures found in the natural world. A decrease in both tonal and broadband noise is seen compared to a normal foil geometry with minimal change in the drag. The mechanism for tonal noise reduction appears to be similar to that seen when using serrations. That is, the surface ridges and trailing edge serrations break-up the two-dimensional tube vortices into three-dimensional vortices.

Much of the research into biomimetic structures for noise reduction is inspired by the structure of owl feathers, which has been a source of inspiration for noise reduction since the 1930s, when Graham (1934) discussed the possibility of using owl feathers as a guide to designing quieter aircraft. A study by Chen et al. (2012) found that the leading edge serrations and trailing edge fringes on owl feathers can reduce the pressure fluctuations, and hence the noise, over the wing. Furthermore, it was also suggested that the porous grid structure over the feather also contributes to sound suppression. Further analysis of the structure of owl feathers and how they suppress sound can be found in Bachmann and Wagner (2011) and Wagner et al. (2017).

This work has inspired both experimental (Clark et al., 2016) and numerical (Wang et al., 2021) studies where airfoil designs are modified to try and mimic some of the feather's features in order to reduce the trailing edge noise. Figs. 6 and 7 show a detailed view of some of the features of the feather that are thought to suppress noise and Fig. 8 shows some of the designs that have been developed to mimic certain features. These designs have all led to modest reductions in airfoil self-noise and could potentially be applied to the reduction of propeller blade trailing edge noise and noise from other rotating machinery such as within HVAC systems.

Another approach, inspired in part by the porous structure of an owl feather, is the use of porous materials over part or all of the geometry (Geyer et al., 2010a,b; Carpio et al., 2019). Porous materials have also been considered computationally, for example Ananthan et al. (2020) where a hybrid LES/APE approach is used to look at trailing edge noise reduction by way of a porous trailing edge. This study identified two mechanisms by which the porous trailing edge reduced the sound pressure level: firstly by reducing the span-wise coherence of the turbulent structures and secondly by reducing the convection velocity of the eddies.

A useful comparison of these approaches for the suppression of trailing edge noise can be found in Vathylakis et al. (2015). Experiments were carried out for a serrated trailing edge as well as different types of porous-serrated trailing edges. The study found that by using a porous-serrated edge, the tonal noise associated with the blunt trailing edge could be suppressed whilst also reducing the broadband noise. However, the effectiveness of the porous surface to reduce broadband noise depended on the specific porosity, which also agreed with the findings of Geyer et al. (2010a), who found that certain levels of porosity increased noise levels at higher frequencies. This was attributed to the roughness effect of the surface. If the flow resistivity of the material is too high, then the material becomes too impermeable and so the benefits are lost.

Despite arising via a very different physical mechanism, research into reducing leading edge noise has considered similar modifications as those made to reduce trailing edge noise. Serrated leading edges have been considered by a number of researchers, including experimentally (Narayanan et al., 2015) and numerically (Kim et al., 2016). In their numerical study, Kim et al. (2016) compared straight leading-edge serrations with wavy serrations and found that the wavy serrations introduced a phase interference which, coupled with the destructive acoustic effects of the geometric obliquity, contributed to a reduced far-field acoustic intensity. Therefore, despite the solution to reducing the noise taking a similar geometric form, the mechanism by which it works is subtly different. For trailing edge noise, a serrated edge acts to break up the coherent turbulent structures resulting in destructive interference and a decreases coherence. Leading edge serrations, on the other hand, reduce the scattering efficiency but they also act to introduce a phase difference in the acoustic waves that result from a vortex impinging on the foil.

One of the unique challenges that arises when considering such technology within the marine environment is fouling. The build-up of marine growth on a propeller or other surface could quickly negate the benefits of porous or serrated edges. Further research into the application of such technology within the marine environment could consider this in more detail, and this also highlights the importance of full-scale trials in realistic environments.

4. Reducing machinery noise

Depending on the power and propulsion architecture, noise from machinery can be the dominant noise source for vessels travelling at lower speeds. As discussed in Section 2, sound and vibration from machinery induces underwater radiated noise by two means: by transmitting vibration into the hull structure via the mounts and by air-borne noise, which induces further vibration in the hull structure. Therefore,

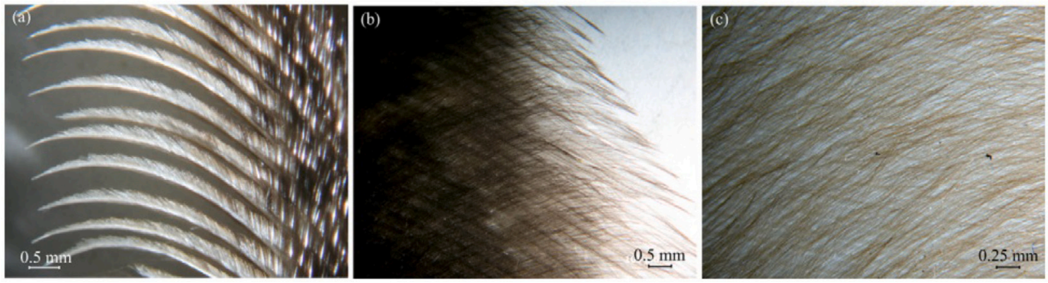


Fig. 6. Images showing the structure of an eagle owl feather.
Source: Reproduced from Chen et al. (2012).

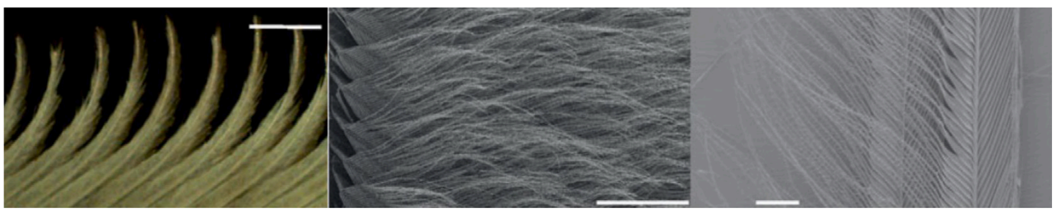
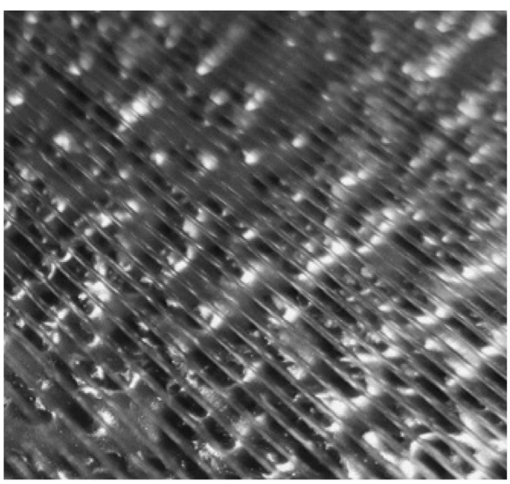


Fig. 7. Images showing the structure of a barn owl feather. Scales, indicated by the white lines in the figures are 1 mm (left and centre) and 200 μm (right).
Source: Reproduced from Wagner et al. (2017).



(a) Porous canopy structure developed by Clark et al. (2016)

(b) Edge serrations on a foil. Reproduced from (Wang et al., 2021)

Fig. 8. Examples of designs inspired by owl feathers to reduce noise.

technologies and designs for reducing the URN from machinery need to target one of these two paths. It should also be noted that the type of machinery, particularly the choice of prime mover, can have a significant impact on the levels of radiated noise, but this is beyond the scope of this paper. Extensive research has been carried out for developing isolation and damping technology for machinery on-board submarines, with the primary motivation being to reduce detection. Howard (2011) provides a good overview of some of the different approaches used on submarines, including passive and active isolators and acoustic tiles.

The manner in which large items of machinery, particularly main engines and generators, are mounted to the primary structure can have a large impact on the resulting levels of URN. Therefore, the design of the mounts is an important consideration. Directly mounting machinery to the primary structure, as is common practice for many commercial vessels, leads to a high level of transmission of the vibration to the shell plating and hence into the surrounding water. The use of vibration isolation mounts is more common on naval vessels and cruise ships, and could be used more widely on commercial vessels of many types. The principles of this are well understood, and detailed descriptions of the theory and design of passive isolation mounts can be found in many textbooks, see Mead (1998), Vér and Beranek (2005) and Long (2005) for example.

Despite the maturity of passive vibration isolators, there are remarkably few studies in open literature that provide a quantitative assessment on how much the underwater noise can be reduced by using this technology. Bonney and Bahtiarian (2006) describe the design of a research vessel that utilises both single and double-stage isolation mounts for the diesel generators and finds that the vessel does meet the ICES standard for reduced noise from fisheries research vessels (Mitson, 1995). However, the actual noise reduction achieved by the mounts is not known. Clearly, carrying out such an experiment is both complex and costly, requiring acoustic or vibration trials to be carried out both on the vessel as designed and without the use of isolation mounts. For naval vessels, it is common practice to carry out a multi-stage process for determining the performance of isolation mounts. Firstly, tests are carried out prior to installation on the ship using a large concrete block with a near-infinite impedance. Following installation on a vessel, harbour trials are then carried out prior to sea trials which determines the radiated noise levels. Numerical methods might perhaps be better utilised here and some studies have considered this. Zheng et al. (2001) use numerical methods investigate the noise contribution from piston-slap and the vibration from vertical inertial forces in a marine diesel engine. This study finds that the excitation from piston-slap is substantial and that, as a result, the rotational stiffness of mounts must also be considered in order to design an effective isolation system. The influence of mount design on the transmission of engine vibrations through a ship structure is also considered by Lin et al. (2009). Here, finite element analysis is used to assess the effectiveness of different mount designs, and it is found that effective isolation of the higher frequency vibrations can be readily improved. However, this is not the case at lower frequencies, with the mounts failing to attenuate vibrations at frequencies below the 1/3 octave band centred at 63 Hz.

Most passive isolators are linear in terms of their force–displacement relationship. However, non-linear passive isolators are also being developed. These can be designed to possess a property known as *chaotification* (Howard, 2011), where a tonal excitation is converted into a broadband signal by the isolator. This is often described as line spectra reduction. An extensive review of non-linear isolators is given by Ibrahim (2008) who discusses the theory, properties, and applications of such devices, including reducing radiated noise from machinery vibration on-board ships. To possess this *chaotic* behaviour, the isolator must have a variable stiffness and damping and studies have shown that substantial reductions in vibration transmission can be achieved. Lou et al. (2005) describe the routes to chaos for such a system and also show that an isolator designed to exhibit a chaotic response is superior to one that does not. Further studies have developed these ideas, with submarine stealth being a key driver (Wen et al., 2009; Li et al., 2011). This technology is far less mature than passive linear isolators, but studies have shown that it has much potential.

The attenuation of low frequency vibrations is a fundamental challenge when designing isolation mounts for large machines. Passive mounts work by having a natural frequency that is considerably lower than the excitation frequency and so isolating low frequency vibrations requires mounts that are too soft. This problem, together with the desire to create more effective isolation systems has led to the development of active devices for machinery vibration isolation. Active isolators work by introducing secondary forces to either reduce or cancel the forces induced by the machinery. This can be achieved through numerous means, including piezoelectric actuators (Pan et al., 2008) and electromagnetic actuators (Daley et al., 2004; Li et al., 2017; Yang et al., 2017). Within submarine design, the use of such technology is more common due to strict URN requirements and the larger budgets generally afforded to such programs. Two-stage isolators, where an active device is used in conjunction with a passive isolator have been developed (Sommerfeldt and Tichy, 1990; Niu et al., 2005) and these can exhibit excellent isolation characteristics at both low and high frequencies. The effectiveness of such technology has been well documented, but there remain challenges to applying it widely to marine vessels, some of which are discussed by Li et al. (2017). In particular, active systems based on either electromagnetic or hydraulic actuators are large compared to passive isolators and require additional power and control systems. This increases the cost and space requirements, limiting their appeal for use on commercial vessels. Further research to reduce the size and complexity of active isolation systems would be welcome and enable wider adoption of such technology within the marine industry.

As well as the mountings used for machinery, it is also worth considering how we can limit the transmission of vibration within the hull structure, and also the airborne noise that induces further vibrations. Traditional methods for absorbing airborne noise and preventing vibration transmission, such as acoustic tiles (Howard, 2011) and mineral wool (Cha and Chun, 2008; Lloyd's Register, 2010) can be effective, particularly for higher frequency noise and vibration. These methods are often used to reduce onboard noise and vibration, particularly on vessels with large passenger or crew numbers, such as cruise ships. As well as these traditional approaches, there is also a relatively new class of materials called acoustic metamaterials that have enormous potential in the fields of sound and vibration control. These are materials designed to manipulate acoustic waves, usually by incorporating carefully designed sub-wavelength structures into composite materials (Haberman and Guild, 2016). They can be used to manipulate wave speeds or bend acoustic waves around a structure rendering it *acoustically invisible*, see Zhang et al. (2011) for example. For the purpose of reducing URN from machinery noise and vibration, there are several areas of metamaterial research that are of considerable interest.

The first is the so-called acoustic black hole (ABH). This was first developed as a theoretical concept by Mironov (1988), where it was shown that flexural waves travelling in a beam terminated by a wedge whose thickness decreases to zero according to some power-law could be slowed down and stopped before they reached the end, thus preventing reflection. If this is combined with some dissipation mechanism, the system has a theoretical reflection coefficient of zero. These ideas were further developed by Krylov and Winward (2007) for two-dimensional structures, such as plates and a detailed review of the theory and potential applications of acoustic black holes is that of Pelat et al. (2020).

There are many areas where such devices could be utilised within marine structures in order to attenuate vibration from machinery before it reaches the shell plating. For example, the use of circular indentations in plates and beams can be highly effective in vibration isolation and a number of experimental and numerical studies have demonstrated this (Bowyer et al., 2013; Deng et al., 2019). The frequencies attenuated by an acoustic black hole are determined by its geometric properties and the material properties of the structure. Experimental studies show that no wave absorption is seen when the frequency of the incident wave is below a cut-on frequency. This will generally be a frequency associated with a wavelength that is much larger than the characteristic length of the ABH, and further details on this are given by Pelat et al. (2020). The physical mechanisms associated with focussing and isolation of flexural waves by the ABH are discussed in a several works, for example Huang et al. (2018). The focussing properties of an acoustic black hole have led to researchers being able to develop semi-passive devices whereby ABHs are used to direct energy towards piezoelectric transducers which extract energy from the system. This technique has been demonstrated experimentally and numerically by Zhao and Semperlotti (2017), who show that this technique is effective over a very wide frequency range.

One of the challenges with using ABHs within marine structures is how to design them so that they are effective at isolating and damping flexural waves whilst retaining the desired structural properties. The most effective design from an isolation perspective leads to the plate thickness becoming infinitely thin in the centre of indentation. Clearly, this will lead to a weak structure and so the trade-off between structural integrity and damping performance needs to be carefully considered.

Damping air-borne noise from machinery and preventing it from inducing shell-plate vibration remains a challenge for marine vessels. Recent advances in materials science have given rise to acoustic absorbing materials that could enable a significant reduction in this component of URN. Aerogels are one such group of materials that have been shown to exhibit extraordinary acoustic damping properties. Detailed descriptions of the physics of acoustic wave absorption by aerogels can be found in Gibiat et al. (1995) and Guild et al. (2016). One such approach is to design a material that reduces the propagation speed to close to zero. This results in so-called "slow-waves", and the use of such a method for acoustic absorption is discussed by Groby et al. (2015). The past few years has seen many advances in this technology, with theoretical, numerical, and experimental studies demonstrating

Table 1
Description of maturity and estimated technology readiness level (TRL) of the technologies discussed.

Technology	Noise source	Description of maturity	TRL
Vortex generator	Sheet and bubble cavitation, blade-rate noise	Widely used in many industries for controlling flow. Experimental and numerical studies demonstrate effectiveness for improving wake uniformity and noise reduction. Performance also demonstrated at full-scale. Effectiveness and optimal design will be vessel specific and future studies should also consider the impact of the self-noise of the vortex generator.	7–9
Water/polymer injection	Tip vortex cavitation	Numerous experimental and numerical studies indicate viability of such an approach but no known full-scale trials at the time of writing.	3–4
Flexible thread	Tip vortex cavitation	Experimental studies at model scale indicate viability of technology. Further studies assessing integration issues and effectiveness at full-scale needed.	3–4
Winglets	Tip vortex cavitation	Widely used in the aerospace sector and the theory is well understood. Some experimental and numerical studies show that winglets can be effective in reducing TVC. Further research needed to understand the overall impact on noise and efficiency.	4–5
Roughness applied to tip/edges	Tip vortex cavitation	Demonstrated numerically and experimentally at model scale. Further research needed to understand the trade-offs between noise reduction and efficiency loss.	3–4
Propeller boss-cap fin/eco-cap	Hub vortex cavitation	Widely used and multiple numerical, experimental and full-scale studies demonstrate their effectiveness at reducing or removing hub vortex cavitation. Noise reduction characteristics associated with this have also been confirmed experimentally.	6–7
Energy-saving devices to reduce propeller rotation rate	Propeller noise (cavitating and non-cavitating)	Multiple experimental studies and full-scale trials demonstrating the effectiveness of such technology for generating thrust and improving propulsive efficiency. However, their impact on noise reduction has not been widely assessed.	1–3
Serrated leading/trailing edges	leading-edge and trailing edge noise	Widely researched and many experimental and numerical studies demonstrate their effectiveness. Technology now utilised in renewable energy sector. Further research needed to understand effectiveness for reducing trailing edge and interaction noise on marine vessels.	4–6
Porous surfaces/edges/tip	Tip vortex cavitation, leading-edge and trailing-edge noise	Numerous experimental and numerical studies show effectiveness in reducing phenomena such as trailing edge noise and TVC. Further research is required to understand how they could be effectively applied to propeller or appendage design and understand impact of fouling on performance.	3–4
Passive isolation mounts	Machinery noise	Well researched technology and used widely on naval and research vessels	9
Nonlinear isolation mounts	Machinery noise	Extensive research across a range of applications. Now used in some industries. Limited application in maritime industry at time of writing	5–7
Active/hybrid isolation mounts	Machinery noise	Extensive research, particularly for naval vessels. Technology is used on submarines	9
Acoustic insulation/mineral wool	Machinery noise	Widely used in many industries (including marine) to reduce vibration transmission and absorb airborne noise	9
Acoustic black hole	Machinery noise	Multiple experimental and numerical studies demonstrating the concept. Limited application within industry/marine design. Research needs to consider integration of ABH within a marine structure.	3–4
Aerogels/metamaterial absorbers	Machinery noise	Analytical and experimental research demonstrating the potential of such technology. Research needed to assess how to apply to a marine vessel and assess integration issues.	3–4
Acoustic duct silencer	Machinery noise, flow noise in ducts and pipes	Very early stages of research and development but this shows much potential for application to hull openings and within exhaust systems.	3

the effectiveness of aerogels in absorbing air-borne noise (Malakooti et al., 2021; Fernández-Marín et al., 2019; Oh et al., 2018; Rapisarda et al., 2021). These materials are lightweight and can be made into any shape desired, making them flexible and greatly increasing their potential applications. Other materials exhibiting similar properties have also been developed, including silicone rubber (Ba et al., 2017) and a polyurethane foam (Park et al., 2017). It has been shown that these materials can either be tuned to different frequency bands or are effective over a wide range of frequencies (Malakooti et al., 2021). They could therefore be utilised in machinery spaces to damp the air- and structure-borne noise from engines, generators and HVAC systems, which could greatly reduce ship-board noise as well as noise radiated into the surrounding ocean.

Another recent development that could have important applications in the maritime sector is the ultra-open acoustic metamaterial silencer (Ghaffarivardavagh et al., 2019). Preventing fluid-borne noise from propagating through a system typically involves isolating the fluid, which is not possible in many applications, for example HVAC systems or ballast systems onboard ships. However, noise from these systems radiates into the surrounding ocean, either indirectly by inducing vibration of the hull shell plating, or directly into the ocean if the system is directly connected to the surrounding water. Structures that attenuate sound whilst still allowing fluid to pass through them have been proposed in a number of works (Kim and Lee, 2014; Chen et al., 2015). However, as noted by Ghaffarivardavagh et al. (2019), the permeability of many of these structures is limited in order to obtain the desired acoustic performance, which makes them unsuitable for application to HVAC systems or ballast systems. Ghaffarivardavagh et al. (2019) develop an acoustic silencer based around a transverse bilayer structure where the two layers have significantly different acoustic impedances which introduces a Fano-like interference. This enables a high level of attenuation whilst maintaining a 60% open area for fluid passage. This could potentially be applied to a variety of ship-board systems including HVAC systems and sea water inlets and outlets, which all contribute to the overall noise radiated from the vessel. However, this technology is very much in its infancy and further research is needed to understand how it could effectively be applied within industry. In particular, the permeability of the structure will impact on the efficiency of the system and this may outweigh the acoustic benefits.

5. Conclusions

In this paper, a range of noise-reducing technologies have been discussed with the aim of assessing how they could be applied to reducing URN from marine vessels. Design methods and technologies for reducing cavitation, flow-induced noise, and machinery noise have all been considered, drawing on a wide range of studies. Technology developed within the maritime sector has been considered as well as technology from the aerospace and renewable energy sectors. The maturity of the technology varies considerably and whilst some could readily be applied today, significant research and development would be needed to advance the technology readiness levels of others.

The review has identified many devices with a high level of maturity that could be applied widely across the industry, without the need for extensive research and development. Passive vibration isolation mounts, vortex generators, improved hullform design, and a wider adoption of energy-saving devices to allow for reduced propeller speed could all have a significant impact on overall noise levels.

The lack of uptake of noise reducing technology can be attributed to a number of factors. Firstly, there are no legally binding requirements for vessels to reduce noise, and an international agreement on this is likely to still be some way off. Secondly, there remains a lack of data that quantitatively determines the reduction in noise achieved by a adopting a particular device. Given the costs of retro-fitting devices or designing new vessels with technology that is perceived to be uncertain and immature, the lack of uptake is perhaps not surprising. Finally, with the exception of devices that also improve energy efficiency, there are currently few economic incentives for ship owners and operators to adopt noise reducing measures. Notable exceptions are the Prince Rupert Port and Port of Vancouver EcoAction programs, where vessels pay reduced harbour fees if they meet certain noise and other environmental criteria. If programs such as this were implemented more widely, then ship operators would be more incentivised to reduce noise. This should, in turn, encourage more research to mature different technologies and carry out more trials to demonstrate noise-reduction. This creates a virtuous circle, as more visibility of these issues together with more research will lead to a wider take-up across the industry.

It is acknowledged that some of the technologies reviewed, particularly the acoustic meta-materials, and some of the measures for reducing fluid-induced noise and tip vortex cavitation are far less mature, but they have shown much promise in experiments and numerical analyses. It should be relatively straightforward to advance the maturity of many of these. The flexible thread, which has been shown to be effective at suppressing tip vortex cavitation in laboratory experiments, could readily be assessed in trials, at least on a small scale, to determine its viability in a more realistic environment. Research must continue with a view to maturing these and assessing the integration and operability issues associated with marine vessels.

An overview of the maturity of the devices discussed in this review is given in Table 1. This provides a brief review of the maturity of each and then assigns an indicative technology readiness level (TRL) based on the definitions given by Olechowski et al. (2015). It should be noted that these levels apply to the devices as applied to the reduction of underwater noise. Some, for example Flettner rotors and kites, are very mature technologies for energy efficiency but there impact on noise reduction has not been quantitatively assessed. Thus, these are assigned a much lower TRL.

As well as maturing some of the technologies discussed here, future research should aim to provide more granularity on the make-up of the acoustic signature of different vessels. This would help to determine which technologies could provide the greatest benefit to reducing the overall noise.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

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References

Abrahamsen, K., 2012. The ship as an underwater noise source. In: Proceedings of Meetings on Acoustics ECUA2012, Vol. 17. Acoustical Society of America, 070058.
Ainslie, M.A., Martin, S.B., Deveau, T.J., MacGillivray, A.O., Bae, C., Wittekind, D., 2021. Towards a standard for vessel URN measurement in shallow water. In: JASCO Applied Sciences.
Ainslie, M.A., Martin, S.B., Trounce, K.B., Hannay, D.E., Eickmeier, J.M., Deveau, T.J., Lucke, K., MacGillivray, A.O., Nolet, V., Borys, P., 2022. International harmonization of procedures for measuring and analyzing of vessel underwater radiated noise. Mar. Pollut. Bull. 174, 113124.
Aktas, B., Yilmaz, N., Atlar, M., Sasaki, N., Fitzsimmons, P., Taylor, D., 2020. Suppression of tip vortex cavitation noise of propellers using PressurePoresTM technology. J. Mar. Sci. Eng. 8 (3), 158.
Amini, A., Reclari, M., Sano, T., Iino, M., Farhat, M., 2019a. Suppressing tip vortex cavitation by winglets. Exp. Fluids 60 (11), 1–15.
Amini, A., Seo, J., Rhee, S.H., Farhat, M., 2019b. Mitigating tip vortex cavitation by a flexible trailing thread. Phys. Fluids 31 (12), 127103.
Ananthan, V.B., Bernicke, P., Akkermans, R., Hu, T., Liu, P., 2020. Effect of porous material on trailing edge sound sources of a lifting airfoil by zonal overset-LES. J. Sound Vib. 480, 115386.
Arndt, R.E., 2002. Cavitation in vortical flows. Annu. Rev. Fluid Mech. 34 (1), 143–175.
Arndt, R., Arakeri, V., Higuchi, H., 1991. Some observations of tip-vortex cavitation. J. Fluid Mech. 229, 269–289.
Arveson, P.T., Vendittis, D.J., 2000. Radiated noise characteristics of a modern cargo ship. J. Acoust. Soc. Am. 107 (1), 118–129.
Asnaghi, A., Svennberg, U., Gustafsson, R., Bensow, R.E., 2020. Investigations of tip vortex mitigation by using roughness. Phys. Fluids 32 (6), 065111.
Asnaghi, A., Svennberg, U., Gustafsson, R., Bensow, R.E., 2021. Propeller tip vortex mitigation by roughness application. Appl. Ocean Res. 106, 102449.
Audoly, C., Rousset, C., Rizzuto, E., Mullor, R.S., Hallander, J., Baudin, E., 2015. Mitigation measures for controlling the ship underwater radiated noise, in the scope of AQUO project. In: OCEANS 2015-Genova. IEEE, pp. 1–6.
Ba, A., Kovalenko, A., Aristégui, C., Mondain-Monval, O., Brunet, T., 2017. Soft porous silicone rubbers with ultra-low sound speeds in acoustic metamaterials. Sci. Rep. 7 (1), 1–6.
Bachmann, T., Wagner, H., 2011. The three-dimensional shape of serrations at barn owl wings: towards a typical natural serration as a role model for biomimetic applications. J. Anat. 219 (2), 192–202.
Bastos, L.P., Deschamps, C.J., da Silva, A.R., 2017. Experimental investigation of the far-field noise due to jet-surface interaction combined with a chevron nozzle. Appl. Acoust. 127, 240–249.
Blake, W.K., 2017. Mechanics of Flow-Induced Sound and Vibration, Volume 2: Complex Flow-Structure Interactions. Academic Press.
Blake, W.K., Wolpert, M., Geib, F., 1977. Cavitation noise and inception as influenced by boundary-layer development on a hydrofoil. J. Fluid Mech. 80 (4), 617–640.
Bonney, D.J., Bahtiarian, M., 2006. Design of a coastal research vessel with low underwater noise signature. In: OCEANS 2006. IEEE, pp. 1–10.
Bowyer, E., O'Boy, D., Krylov, V.V., Gautier, F., 2013. Experimental investigation of damping flexural vibrations in plates containing tapered indentations of power-law profile. Appl. Acoust. 74 (4), 553–560.
Brennen, C., 1970. Some cavitation experiments with dilute polymer solutions. J. Fluid Mech. 44 (1), 51–63.
Brooks, T.F., Pope, D.S., Marcolini, M.A., 1989. Airfoil self-noise and prediction. NASA Rep..
Burrill, L., Emerson, A., 1963. Propeller cavitation: Further tests on 16 in. propeller models in the King's college cavitation tunnel. Int. Shipbuild. Prog. 10 (104), 119–131.
Callender, B., Gutmark, E., Martens, S., 2005. Far-field acoustic investigation into chevron nozzle mechanisms and trends. AIAA J. 43 (1), 87–95.
Carlton, J., Vlasic, D., 2005. Ship vibration and noise: some topical aspects. In: Proceedings of the 1st International Ship Noise and Vibration Conference. pp. 1–11.

Carpio, A.R., Martinez, R.M., Avallone, F., Ragni, D., Snellen, M., van der Zwaag, S., 2019. Experimental characterization of the turbulent boundary layer over a porous trailing edge for noise abatement. J. Sound Vib. 443, 537–558.
Cha, S.-I., Chun, H.-H., 2008. Insertion loss prediction of floating floors used in ship cabins. Appl. Acoust. 69 (10), 913–917.
Chahine, G., Frederick, G., Bateman, R., 1993. Propeller tip vortex cavitation suppression using selective polymer injection. J. Fluids Eng. 115, 497–503.
Chang, N., Ganesh, H., Yakushiji, R., Ceccio, S.L., 2011. Tip vortex cavitation suppression by active mass injection. J. Fluids Eng. 133 (11).
Chen, Z., Fan, L., Zhang, S.-y., Zhang, H., Li, X.-j., Ding, J., 2015. An open-structure sound insulator against low-frequency and wide-band acoustic waves. Appl. Phys. Express 8 (10), 107301.
Chen, K., Liu, Q., Liao, G., Yang, Y., Ren, L., Yang, H., Chen, X., 2012. The sound suppression characteristics of wing feather of owl (bubo bubo). J. Bionic Eng. 9 (2), 192–199.
Chen, L., Shunhuai, C., Yigong, W., 2010. Analysis on sail selection and energy conservation of a panamax bulk carrier. In: 2010 International Conference on Advances in Energy Engineering. IEEE, pp. 182–185.
Chen, L., Zhang, L., Peng, X., Shao, X., 2019. Influence of water quality on the tip vortex cavitation inception. Phys. Fluids 31 (2), 023303.
Choi, J., Ceccio, S.L., 2007. Dynamics and noise emission of vortex cavitation bubbles. J. Fluid Mech. 575, 1–26.
Chong, T.P., Joseph, P.F., 2013. An experimental study of airfoil instability tonal noise with trailing edge serrations. J. Sound Vib. 332 (24), 6335–6358.
Chou, E., Southall, B.L., Robards, M., Rosenbaum, H.C., 2021. International policy, recommendations, actions and mitigation efforts of anthropogenic underwater noise. Ocean Coast. Manage. 202, 105427.
Clark, I.A., Daly, C.A., Devenport, W., Alexander, W.N., Peake, N., Jaworski, J.W., Glegg, S., 2016. Bio-inspired canopies for the reduction of roughness noise. J. Sound Vib. 385, 33–54.
Cope, S., Hines, E., Bland, R., Davis, J.D., Tougher, B., Zetterlind, V., 2021. Multi-sensor integration for an assessment of underwater radiated noise from common vessels in San Francisco bay. J. Acoust. Soc. Am. 149 (4), 2451–2464.
Daley, S., Johnson, F., Pearson, J., Dixon, R., 2004. Active vibration control for marine applications. Control Eng. Pract. 12 (4), 465–474.
Dang, J., 2004. Improving cavitation performance with new blade sections for marine propellers. Int. Shipbuild. Prog. 51 (4), 353–376.
Deng, J., Guasch, O., Zheng, L., 2019. Ring-shaped acoustic black holes for broadband vibration isolation in plates. J. Sound Vib. 458, 109–122.
Ebrahimi, A., Razaghian, A., Seif, M., Zahedi, F., Nouri-Borujerdi, A., 2019. A comprehensive study on noise reduction methods of marine propellers and design procedures. Appl. Acoust. 150, 55–69.
Fernández-Marín, A.A., Jiménez, N., Groby, J.-P., Sánchez-Dehesa, J., Romero-García, V., 2019. Aerogel-based metasurfaces for perfect acoustic energy absorption. Appl. Phys. Lett. 115 (6), 061901.
Fischer, R., 2008. Singing propellers—solutions and case histories. Mar. Technol. SNAME News 45 (04), 221–227.
Foeth, E.-J., van Terwisga, T., van Doorne, C., 2008. On the collapse structure of an attached cavity on a three-dimensional hydrofoil. J. Fluids Eng. 130 (7).
Franc, J.-P., Michel, J.-M., 2006. Fundamentals of Cavitation, Vol. 76. Springer science & Business media.
Fruman, D., Aflalo, S., 1989. Tip vortex cavitation inhibition by drag-reducing polymer solutions. J. Fluids Eng. (2), 211–216.
Gaggero, S., Gonzalez-Adalid, J., Sobrino, M.P., 2016. Design and analysis of a new generation of CLT propellers. Appl. Ocean Res. 59, 424–450.
Gao, H., Zhu, W., Liu, Y., Yan, Y., 2019. Effect of various winglets on the performance of marine propeller. Appl. Ocean Res. 86, 246–256.
Geyer, T., Sarradj, E., Fritzsche, C., 2010a. Measurement of the noise generation at the trailing edge of porous airfoils. Exp. Fluids 48 (2), 291–308.
Geyer, T., Sarradj, E., Fritzsche, C., 2010b. Porous airfoils: noise reduction and boundary layer effects. Int. J. Aeroacoust. 9 (6), 787–820.
Ghaffarivardavagh, R., Nikolajczyk, J., Anderson, S., Zhang, X., 2019. Ultra-open acoustic metamaterial silencer based on Fano-like interference. Phys. Rev. B 99 (2), 024302.
Gibiat, V., Lefeuvre, O., Woignier, T., Pelous, J., Phalippou, J., 1995. Acoustic properties and potential applications of silica aerogels. J. Non-Cryst. Solids 186, 244–255.
Graham, R., 1934. The silent flight of owls. Aeronaut. J. 38 (286), 837–843.
Groby, J.-P., Huang, W., Lardeau, A., Aurégan, Y., 2015. The use of slow waves to design simple sound absorbing materials. J. Appl. Phys. 117 (12), 124903.
Guild, M.D., García-Chocano, V.M., Sánchez-Dehesa, J., Martin, T.P., Calvo, D.C., Orris, G.J., 2016. Aerogel as a soft acoustic metamaterial for airborne sound. Phys. Rev. A 5 (3), 034012.
Haberman, M.R., Guild, M.D., 2016. Acoustic metamaterials. Phys. Today 69 (6), 42–48.
Hallander, J., Karlsson, R., Johansson, A., 2015. Assessment of underwater radiated noise, cavitation and fuel efficiency for a chemical tanker. In: OCEANS'15.
Hansen, H.R., Dinham-Peren, T., Nojiri, T., 2011. Model and full scale evaluation of a 'propeller boss cap fins' device fitted to an aframax tanker. In: Second International Symposium on Marine Propulsors.
Hermannsen, L., Mikkelsen, L., Tougaard, J., Beedholm, K., Johnson, M., Madsen, P.T., 2019. Recreational vessels without automatic identification system (AIS) dominate anthropogenic noise contributions to a shallow water soundscape. Sci. Rep. 9 (1), 1–10.
Hildebrand, J.A., 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser. 395, 5–20.
Howard, C.Q., 2011. Recent developments in submarine vibration isolation and noise control. In: Proceedings of the 1st Submarine Science Technology and Engineering Conference, Vol. 17. pp. 1–7.
Hu, Y.-S., Wan, Z.-H., Ye, C.-C., Sun, D.-J., Lu, X.-Y., 2022. Noise reduction mechanisms for insert-type serrations of the NACA-0012 airfoil. J. Fluid Mech. 941.
Huang, B., Ducoin, A., Young, Y.L., 2013. Physical and numerical investigation of cavitating flows around a pitching hydrofoil. Phys. Fluids 25 (10), 102109.
Huang, W., Ji, H., Qiu, J., Cheng, L., 2018. Analysis of ray trajectories of flexural waves propagating over generalized acoustic black hole indentations. J. Sound Vib. 417, 216–226.
Ianniello, S., Muscari, R., Di Mascio, A., 2013. Ship underwater noise assessment by the acoustic analogy. Part I: nonlinear analysis of a marine propeller in a uniform flow. J. Mar. Sci. Technol. 18 (4), 547–570.
Ibrahim, R., 2008. Recent advances in nonlinear passive vibration isolators. J. Sound Vib. 314 (3–5), 371–452.
Ji, B., Luo, X., Wu, Y., 2014. Unsteady cavitation characteristics and alleviation of pressure fluctuations around marine propellers with different skew angles. J. Mech. Sci. Technol. 28 (4), 1339–1348.
Jirasek, A., 2005. Vortex-generator model and its application to flow control. J. Aircr. 42 (6), 1486–1491.
Jones, L., Sandberg, R., 2012. Acoustic and hydrodynamic analysis of the flow around an aerofoil with trailing-edge serrations. J. Fluid Mech. 706, 295.
Kaplan, M.B., Solomon, S., 2016. A coming boom in commercial shipping? The potential for rapid growth of noise from commercial ships by 2030. Mar. Policy 73, 119–121.
Kawamura, T., Ouchi, K., Nojiri, T., 2012. Model and full scale CFD analysis of propeller boss cap fins (PBCF). J. Mar. Sci. Technol. 17 (4), 469–480.
Keller, J., Kumar, P., Mahesh, K., 2018. Examination of propeller sound production using large eddy simulation. Phys. Rev. Fluids 3 (6), 064601.
Kim, J.-H., Choi, J.-E., Choi, B.-J., Chung, S.-H., Seo, H.-W., 2015. Development of energy-saving devices for a full slow-speed ship through improving propulsion performance. Int. J. Nav. Archit. Ocean Eng. 7 (2), 390–398.
Kim, J.W., Haeri, S., Joseph, P.F., 2016. On the reduction of aerofoil-turbulence interaction noise associated with wavy leading edges. J. Fluid Mech. 792, 526–552.
Kim, S.-H., Lee, S.-H., 2014. Air transparent soundproof window. AIP Adv. 4 (11), 117123.
Krüger, C., Kornev, N., Greitsch, L., 2016. Influence of propeller tip roughness on tip vortex strength and propeller performance. Ship Technol. Res. 63 (2), 110–120.
Krylov, V.V., Winward, R., 2007. Experimental investigation of the acoustic black hole effect for flexural waves in tapered plates. J. Sound Vib. 300 (1–2), 43–49.
Kuiper, G., 1998. Cavitation research and ship propeller design. Appl. Sci. Res. 58 (1), 33–50.
Kuiper, G., Van Terwisga, T., Zondervan, G., Jessup, S., 2006. Cavitation inception tests on a systematic series of two bladed propellers. In: Delft University of Technology, Ship Hydromechanics Laboratory, Department of Marine Technology, Report No. 1565-P, Paper Presented at the 26th Symposium on Naval Hydrodynamics, Rome, Italy, 17-22 September 2006.
Lalander, E., Svedendahl, M., Nordström-Larsson, R., Johansson, T., Andersson, M.H., 2021. The underwater soundscape in the port of gothenburg and estimations of the underwater radiated noise from ships. In: FOI. p. 26.
Leaper, R., Renilson, M., Ryan, C., 2014. Reducing underwater noise from large commercial ships: current status and future directions.. J. Ocean Technol. 9 (1).
Lee, C.-S., Ahn, B.-K., Han, J.-M., Kim, J.-H., 2018. Propeller tip vortex cavitation control and induced noise suppression by water injection. J. Mar. Sci. Technol. 23 (3), 453–463.
Lee, T., Choi, S., 2015. Wingtip vortex control via tip-mounted half-delta wings of different geometric configurations. J. Fluids Eng. 137 (12).
Lee, T., Su, Y., 2012. Wingtip vortex control via the use of a reverse half-delta wing. Exp. Fluids 52 (6), 1593–1609.
Li, D.-Q., Hallander, J., Johansson, T., 2018. Predicting underwater radiated noise of a full scale ship with model testing and numerical methods. Ocean Eng. 161, 121–135.
Li, Y., He, L., Shuai, C.-g., Wang, C.-y., 2017. Improved hybrid isolator with maglev actuator integrated in air spring for active-passive isolation of ship machinery vibration. J. Sound Vib. 407, 226–239.
Li, Y., Xu, D., Fu, Y., Zhou, J., 2011. Stability and chaotification of vibration isolation floating raft systems with time-delayed feedback control. Chaos 21 (3), 033115.
Li, L., Zhou, B., Huang, H., Sun, H., 2021. Vortex generator design and numerical investigation for wake non-uniformity and cavitation fluctuation pressure reduction. Ocean Eng. 229, 108965.
Lin, J.C., 2002. Review of research on low-profile vortex generators to control boundary-layer separation. Prog. Aerosp. Sci. 38 (4–5), 389–420.
Lin, T.R., Pan, J., O'Shea, P.J., Mechefske, C.K., 2009. A study of vibration and vibration control of ship structures. Mar. Struct. 22 (4), 730–743.

Lloyd's Register, O., 2010. Noise from Ships in Ports: Possibilities for Noise Reduction. Danish Environmental Protection Agency.
Long, M., 2005. Architectural Acoustics. Elsevier.
Lou, J.-j., Zhu, S.-j., He, L., Yu, X., 2005. Application of chaos method to line spectra reduction. J. Sound Vib. 3 (286), 645–652.
MacGillivray, A.O., Li, Z., Hannay, D.E., Trounce, K.B., Robinson, O.M., 2019. Slowing deep-sea commercial vessels reduces underwater radiated noise. J. Acoust. Soc. Am. 146 (1), 340–351.
Malakooti, S., Hatamleh, M.I., Zhang, R., Taghvaee, T., Miller, M., Ren, Y., Xiang, N., Qian, D., Sotiriou-Leventis, C., Leventis, N., et al., 2021. Metamaterial-like aerogels for broadband vibration mitigation. Soft Matter 17 (17), 4496–4503.
Markus, T., Sánchez, P.P.S., 2018. Managing and regulating underwater noise pollution. In: Handbook on Marine Environment Protection. Springer, pp. 971–995.
McIntyre, D., Lee, W., Frouin-Mouy, H., Hannay, D., Oshkai, P., 2021. Influence of propellers and operating conditions on underwater radiated noise from coastal ferry vessels. Ocean Eng. 232, 109075.
McKenna, M.F., Ross, D., Wiggins, S.M., Hildebrand, J.A., 2012. Underwater radiated noise from modern commercial ships. J. Acoust. Soc. Am. 131 (1), 92–103.
Mead, D.J., 1998. Passive Vibration Control. John Wiley & Sons.
Merchant, N.D., 2019. Underwater noise abatement: Economic factors and policy options. Environ. Sci. Policy 92, 116–123.
Mickle, M.F., Higgs, D.M., 2018. Integrating techniques: a review of the effects of anthropogenic noise on freshwater fish. Can. J. Fish. Aquat. Sci. 75 (9), 1534–1541.
Mironov, M., 1988. Propagation of a flexural wave in a plate whose thickness decreases smoothly to zero in a finite interval. Sov. Phys. Acoust. USSR 34 (3), 318–319.
Mitson, R., 1995. Underwater noise of research vessels: review and recommendations. In: ICES. p. 61.
Mizzi, K., Demirel, Y.K., Banks, C., Turan, O., Kaklis, P., Atlar, M., 2017. Design optimisation of propeller boss cap fins for enhanced propeller performance. Appl. Ocean Res. 62, 210–222.
Molland, A.F., Turnock, S.R., Hudson, D.A., 2017. Ship Resistance and Propulsion. Cambridge University Press.
Moreau, D.J., Doolan, C.J., 2013. Noise-reduction mechanism of a flat-plate serrated trailing edge. AIAA J. 51 (10), 2513–2522.
Moreno, A., Salinas, R., Audoly, C., Rousset, C., Beltrán, P., Rizzuto, E., Gaggero, T., Hallander, J., Li, D.-Q., 2015. AQUO: achieve quieter oceans by shipping noise footprint reduction, WP2: noise sources, task T2.5.
Murchy, K.A., Davies, H., Shafer, H., Cox, K., Nikolich, K., Juanes, F., 2019. Impacts of noise on the behavior and physiology of marine invertebrates: A meta-analysis. In: Proceedings of Meetings on Acoustics 5ENAL, Vol. 37. Acoustical Society of America, 040002.
Narayanan, S., Chaitanya, P., Haeri, S., Joseph, P., Kim, J., Polacsek, C., 2015. Airfoil noise reductions through leading edge serrations. Phys. Fluids 27 (2), 025109.
Niu, J., Song, K., Lim, C., 2005. On active vibration isolation of floating raft system. J. Sound Vib. 285 (1–2), 391–406.
Nowacek, D.P., Thorne, L.H., Johnston, D.W., Tyack, P.L., 2007. Responses of cetaceans to anthropogenic noise. Mammal Rev. 37 (2), 81–115.
Oh, J.-H., Kim, J., Lee, H., Kang, Y., Oh, I.-K., 2018. Directionally antagonistic graphene oxide-polyurethane hybrid aerogel as a sound absorber. ACS Appl. Mater. Interfaces 10 (26), 22650–22660.
Okada, Y., Kawasaki, M., Katayama, K., Okazaki, A., Fukuda, K., Okazaki, M., 2015. The development of "ultimate rudder" for EEDI. In: MARINE VI: Proceedings of the VI International Conference on Computational Methods in Marine Engineering. CIMNE, pp. 605–612.
Olechowski, A., Eppinger, S.D., Joglekar, N., 2015. Technology readiness levels at 40: A study of state-of-the-art use, challenges, and opportunities. In: 2015 Portland International Conference on Management of Engineering and Technology (PICMET). IEEE, pp. 2084–2094.
Ouchi, K., Tamashima, M., Kawasaki, T., Koizuka, H., 1989. A research and development of PBCF (propeller boss cap fins) 2nd report: Study on propeller slipstream and actual ship performance. J. Soc. Nav. Archit. Japan 1989 (165), 43–53.
Pan, X., Tso, Y., Juniper, R., 2008. Active control of low-frequency hull-radiated noise. J. Sound Vib. 313 (1–2), 29–45.
Park, H.-S., Choi, S.-H., Kim, N.-S., 2005. Identification of propeller singing phenomenon through vibration analysis of propeller blade. In: The Fifteenth International Offshore and Polar Engineering Conference. OnePetro.
Park, S.-I., Lee, S.-J., You, G.-S., Suh, J.-C., 2014. An experimental study on tip vortex cavitation suppression in a marine propeller. J. Ship Res. 58 (3), 157–167.
Park, J.H., Minn, K.S., Lee, H.R., Yang, S.H., Yu, C.B., Pak, S.Y., Oh, C.S., Song, Y.S., Kang, Y.J., Youn, J.R., 2017. Cell openness manipulation of low density polyurethane foam for efficient sound absorption. J. Sound Vib. 406, 224–236.
Park, S., Oh, G., Rhee, S.H., Koo, B.-Y., Lee, H., 2015. Full scale wake prediction of an energy saving device by using computational fluid dynamics. Ocean Eng. 101, 254–263.
Pelat, A., Gautier, F., Conlon, S.C., Semperlotti, F., 2020. The acoustic black hole: A review of theory and applications. J. Sound Vib. 476, 115316.
Pham, T.M., Larrarte, F., Fruman, D.H., 1999. Investigation of unsteady sheet cavitation and cloud cavitation mechanisms. J. Fluids Eng. 121 (2), 289–296.
Qin, D., Pan, G., Lee, S., Huang, Q., Shi, Y., 2019. Underwater radiated noise reduction technology using sawtooth duct for pumpjet propulsor. Ocean Eng. 188, 106228.
Rapisarda, M., Fierro, G.-P.M., Meo, M., 2021. Ultralight graphene oxide/polyvinyl alcohol aerogel for broadband and tuneable acoustic properties. Sci. Rep. 11 (1), 1–10.
Reinikainen, K., 2021. Thruster noise spotlighted by smaller cruise ships. Nav. Archit. 64–65.
Richardson, W., Greene, Jr., C., Malme, C., Thomson, D., 1995. Marine mammal hearing. Mar. Mammals Noise 205–240.
Rizzuto, E., Villa, D., Gaggero, S., Kellett, P., Haimov, E., Molinelli, E., J, H., D-Q, L., 2015. AQUO: achieve quieter oceans by shipping noise footprint reduction, WP2: noise sources.
Salinas, R., Moreno, A., 2014. AQUO: achieve quieter oceans by shipping noise footprint reduction, WP3: measurements.
Saydam, A.Z., Gokcay, S., Insel, M., 2018. CFD based vortex generator design and full-scale testing for wake non-uniformity reduction. Ocean Eng. 153, 282–296.
Seo, J., Lee, S.J., Han, B., Rhee, S.H., 2016. Influence of design parameter variations for propeller-boss-cap-fins on hub vortex reduction. J. Ship Res. 60 (4), 203–218.
Shin, H.-J., Lee, J.-S., Lee, K.-H., Han, M.-R., Hur, E.-B., Shin, S.-C., 2013. Numerical and experimental investigation of conventional and un-conventional preswirl duct for VLCC. Int. J. Nav. Archit. Ocean Eng. 5 (3), 414–430.
Simmonds, M.P., Dolman, S.J., Jasny, M., Parsons, E., Weilgart, L., Wright, A.J., Leaper, R., 2014. Marine noise pollution-increasing recognition but need for more practical action. J. Ocean Technol. 9, 71–90.
Simpson, S.D., Radford, A.N., Nedelec, S.L., Ferrari, M.C., Chivers, D.P., McCormick, M.I., Meekan, M.G., 2016. Anthropogenic noise increases fish mortality by predation. Nature Commun. 7 (1), 1–7.
Sommerfeldt, S.D., Tichy, J., 1990. Adaptive control of a two-stage vibration isolation mount. J. Acoust. Soc. Am. 88 (2), 938–944.
Spence, J.H., Fischer, R.W., 2016. Requirements for reducing underwater noise from ships. IEEE J. Ocean. Eng. 42 (2), 388–398.
Su, Y.-m., Lin, J.-f., Zhao, D.-g., Guo, C.-y., Guo, H., 2020. Influence of a pre-swirl stator and rudder bulb system on the propulsion performance of a large-scale ship model. Ocean Eng. 218, 108189.
Sun, Y., Su, Y., Wang, X., Hu, H., 2016. Experimental and numerical analyses of the hydrodynamic performance of propeller boss cap fins in a propeller-rudder system. Eng. Appl. Comput. Fluid Mech. 10 (1), 145–159.
Svennberg, U., Asnaghi, A., Gustafsson, R., Bensow, R.E., 2020. New insights into roughness applications in tip vortex cavitation inception mitigation. In: 33rd Symposium on Naval Hydrodynamics, Osaka, Japan.
Tachikawa, T., Okada, Y., Katayama, K., Okazaki, A., Okazaki, M., Fukuda, K., Kobayashi, Y., Kajino, T., 2019. Efficiency improvement effect and water noise reduction by energy saving devices. In: MARINE VIII: Proceedings of the VIII International Conference on Computational Methods in Marine Engineering. CIMNE, pp. 615–624.
Tani, G., Viviani, M., Rizzuto, E., 2015. Model scale investigation of the effect of different speed reduction strategies on cavitating propeller radiated noise. In: OCEANS 2015-Genova. IEEE, pp. 1–8.
van Terwisga, T., van Wijngaarden, E., Bosschers, J., Kuiper, G., 2007. Achievements and challenges in cavitation research on ship propellers. Int. Shipbuild. Prog. 54 (2–3), 165–187.
Traut, M., Gilbert, P., Walsh, C., Bows, A., Filippone, A., Stansby, P., Wood, R., 2014. Propulsive power contribution of a kite and a flettner rotor on selected shipping routes. Appl. Energy 113, 362–372.
Vakili, S., Ölçer, A., Ballini, F., 2020. The development of a policy framework to mitigate underwater noise pollution from commercial vessels: The role of ports. Mar. Policy 120, 104132.
Van de Voorde, C., 1960. The singing of ship propellers. Int. Shipbuild. Prog. 7 (75), 451–455.
Vard, 2019. Ship underwater radiated noise.
Vathylakis, A., Chong, T.P., Joseph, P.F., 2015. Poro-serrated trailing-edge devices for airfoil self-noise reduction. AIAA J. 53 (11), 3379–3394.
Vér, I.L., Beranek, L.L., 2005. Noise and Vibration Control Engineering: Principles and Applications. John Wiley & Sons.
Wagner, H., Weger, M., Klaas, M., Schröder, W., 2017. Features of owl wings that promote silent flight. Interface Focus 7 (1), 20160078.
Wale, M.A., Simpson, S.D., Radford, A.N., 2013. Noise negatively affects foraging and antipredator behaviour in shore crabs. Anim. Behav. 86 (1), 111–118.
Wang, L., Liu, X., Li, D., 2021. Noise reduction mechanism of airfoils with leading-edge serrations and surface ridges inspired by owl wings. Phys. Fluids 33 (1), 015123.
Wang, J., Zhang, C., Wu, Z., Wharton, J., Ren, L., 2017. Numerical study on reduction of aerodynamic noise around an airfoil with biomimetic structures. J. Sound Vib. 394, 46–58.
Weilgart, L.S., 2007. The impacts of anthropogenic ocean noise on cetaceans and implications for management. Can. J. Zool. 85 (11), 1091–1116.
Wen, G., Lu, Y., Zhang, Z., Ma, C., Yin, H., Cui, Z., 2009. Line spectra reduction and vibration isolation via modified projective synchronization for acoustic stealth of submarines. J. Sound Vib. 324 (3–5), 954–961.
Williams, R., Wright, A.J., Ashe, E., Blight, L., Bruintjes, R., Canessa, R., Clark, C., Cullis-Suzuki, S., Dakin, D., Erbe, C., et al., 2015. Impacts of anthropogenic noise on marine life: Publication patterns, new discoveries, and future directions in research and management. Ocean Coast. Manage. 115, 17–24.

Xin, D., Zhang, H., Ou, J., 2018. Experimental study on mitigating vortex-induced vibration of a bridge by using passive vortex generators. J. Wind Eng. Ind. Aerodyn. 175, 100–110.
Yakhina, G., Roger, M., Jondeau, E., Golubev, V., Nguyen, L., 2015. Parametric investigations of tonal trailing-edge noise generation by moderate Reynolds number airfoils. Part I–experimental studies. In: AIAA Paper 2015.
Yang, B., Hu, Y., Vicario, F., Zhang, J., Song, C., 2017. Improvements of magnetic suspension active vibration isolation for floating raft system. Int. J. Appl. Electromagn. Mech. 53 (2), 193–209.
Zeng, Z.-b., Kuiper, G., 2012. Blade section design of marine propellers with maximum cavitation inception speed. J. Hydrodyn. 24 (1), 65–75.
Zhang, S., Xia, C., Fang, N., 2011. Broadband acoustic cloak for ultrasound waves. Phys. Rev. Lett. 106 (2), 024301.
Zhao, L., Semperlotti, F., 2017. Embedded acoustic black holes for semi-passive broadband vibration attenuation in thin-walled structures. J. Sound Vib. 388, 42–52.
Zheng, H., Liu, G., Tao, J., Lam, K., 2001. FEM/BEM analysis of diesel piston-slap induced ship hull vibration and underwater noise. Appl. Acoust. 62 (4), 341–358.
Zondervan, G., Holtrop, J., Windt, J., Van Terwisga, T., 2011. On the design and analysis of pre-swirl stators for single and twin screw ships. In: Second International Symposium on Marine Propulsors, Hamburg, Germany.