Awareness of underwater noise generated from shipping is rising due to environmental concerns in sensitive areas with protected animal species as well as for the world’s oceans as a whole. Individuals interested in underwater noise have attempted to better understand the problem by performing measurements of vessel noise either by direct measurement or by recording sound levels in different oceans over time. These efforts provide insights into noise levels produced by vessels as well as the noise levels produced by shipping in different locations. However, in order to reduce underwater noise the specific causes of noise must first be identified. Various generalities of primary noise sources and radiation mechanisms can be given for different ship types, though in order to actually reduce noise the structural and machinery details of each ship must be known and considered as part of an acoustical design (or re-design) effort. Specific noise control treatments can be optimized to different vessel designs using various computer-aided tools, though in order to make a significant impact on noise in the world’s oceans such efforts should be performed during the design of any new vessel.

1. Introduction

Airborne noise on ships has been a concern for decades; airborne noise limits such as those adopted by the International Maritime Organization (IMO) [1] have been implemented on many vessels to improve communication and reduce hearing loss among crewmembers. Underwater noise from ships has historically been less of a concern (with the exception of military applications) until recently when its possible impact on the marine environment has become more obvious.

In 2004 the U.S. National Oceanographic and Atmospheric Administration (NOAA) held a symposium to discuss underwater noise from shipping, including causes, effects, and possible mitigation approaches [2]. This was followed in 2007 by a second NOAA symposium [3], and a workshop in 2008 organized by Okeanos [4]. These events were attended by representatives from government, shipping industry, oil and gas industry, biologists, marine acousticians and designers, and others. Similar events have followed in subsequent years, and groups ranging from Green Marine to IMO have been working to increase awareness of underwater noise in the marine community. It appears that the marine community is listening; in 2014 IMO announced (non-mandatory) guidelines for reducing underwater noise from commercial ships which discusses possible approaches to reducing underwater noise from ships [5].

Although there is significant difficulty in understanding hearing capabilities and damage mechanisms in the various species that inhabit the world’s oceans, progress has been made towards defining limits and goals for underwater noise. Many papers have been published presenting studies on animal behavior in the presence of various man-made sounds (including vessel noise), hearing capabilities in marine species, and other related topics. NOAA has also recently issued a “Draft Guidance for
Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing,” which discusses acoustic thresholds for various animal species and impact types (permanent and temporary threshold shifts)[6].

In order to reduce noise and meet current or possible future noise regulations, an understanding of vessel noise must be achieved. Many measurements of individual vessels have been made and are published in the literature; a few examples are [7-12]. There have also been assessments of noise produced by ‘vessels of opportunity’ in a particular area, using AIS or other techniques to estimate distance, vessel type, etc. [13-14]. These measurements are valuable for assessing the degree to which different vessels raise ambient levels, determining potential impacts to marine life, and gaining a general understanding of how vessels can influence underwater noise levels. In certain circumstances, they can even be used to identify a particular source that is dominant or causing a notable feature in the noise spectrum.

However, these measurements alone cannot be used to solve noise problems using an engineering approach. Detailed information about each individual vessel is required in order to gain an understanding of the mechanisms that are causing noise, and to make the design decisions required to reduce noise. Fortunately, the methodology required to gain this understanding is currently available has been implemented on vessels for decades. Improvements to these technologies continue to evolve. Reductions in vessel noise are possible for nearly any vessel type, though the ‘cost’, either in real currency or other factors, must be understood.

A simple example of the potential for vessel quieting is presented in Fig 1. In this example, the radiated noise spectra for two vessels travelling at nearly 11 knots are presented (data is scaled to a 1 meter ‘source level’). One vessel is a cruise ship, with presumably little to no consideration for underwater noise, but with significant consideration of airborne noise1. The other is a fisheries research vessel, with stringent underwater radiated noise goals and considerable effort in the acoustic design and construction. There is a 20-30 dB difference in the radiated noise between these vessels, which results from reductions in both propeller and machinery induced noise.

This comparison is not entirely fair or representative of what is possible when any vessel is designed to be quiet. The cruise ship has different non-acoustical factors than the research vessel which drive the potential for noise control. However, this comparison does show that techniques for noise control exist and are available today, and can be applied to any vessel. This paper attempts to bridge the gap between those who are interested in reducing noise from ships and those who know how it can be done by highlighting available noise control methods and identifying expected noise reductions and costs, when possible.

Note that it is not the intention of this paper to identify appropriate noise criteria. However, it is important to recognize that noise control solutions may be different for different noise goals, depending on the controlling sources and the frequency spectra of the noise they produce.

2. Propeller Noise

2.1 Overview

For many commercial vessels, propeller induced cavitation noise is likely to be one of the dominant sources of noise. Cavitation refers to the generation of vapor bubbles (‘cavities’) within the water when the pressure is reduced below the vapor pressure limit. When a propeller blade rotates through the water, it creates a suction on one side and a (positive) pressure on the other, creating a net pressure differential across the blade. This pressure differential is what propellers the ship, though it is the reduction of pressure on the suction side that can lead to cavitation. A diagram illustrating this principle is presented in Fig 2. Note that the upper area of the diagram presents the suction, or reduced pressure, side, with a particular region passing the vapor pressure limit.

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1 Note that the presented levels are not uncommon for cruise vessels as well as other large vessels, as discussed in [8].
Cavitation bubbles form and then collapse rapidly; this generates noise in the water. The noise is omnidirectional (ignoring effects of the propeller or ship) and is broadband — i.e. there are contributions at all frequencies. Fig 3 presents a general spectrum (with 1-Hz bandwidth) for propeller-induced cavitation [17]. The spectrum has a broad peak in the frequency range of 40-300 Hz, with ‘tones’ occurring at blade rate (shaft rotation rate multiplied by the number of blades) and harmonics. At frequencies above 300 Hz the spectral level decays at roughly 6 dB per octave. The specific spectrum that is generated for a particular ship depends on many factors related to the propeller and vessel design that determine the ‘type’ of cavitation that is occurring (blade surface, tip vortex, etc.).
Generally speaking, there will be more cavitation, and noise, when a vessel is moving faster through the water (under free route conditions), for towing operations, when using thrusters for dynamic positioning, icebreaking, and other conditions that impose high loads on the propulsor.

While these generalities are useful in understanding how propeller cavitation can influence the total noise from a vessel, it is necessary to gain an understanding of the specific mechanics of how propellers generate cavitation in order to be able to reduce cavitation noise. This topic is highly detailed and can lead to years of study of hydrodynamic theory; this paper will only scratch the surface to illustrate the salient points.

2.2 Blade and Wake Design

A propeller blade is essentially a rotating wing that operates in water. Similar to an airplane wing, the primary forces that are used to move the vessel are the suction forces (note that the magnitude of the total suction force in Fig 2 is greater than the pressure force). The suction (and pressure) forces seen in Fig 2 are generated as a result of fluid moving over the blade. The pressures can be contoured by changing the shape of the blade. Additional changes to the pressure distribution can occur if the blade were rotated relative to the direction of motion of the fluid; this is referred to as “angle of attack”, and is illustrated in Fig 4. In the case of Fig 2, rotating the blade counter clockwise would tend to increase the suction forces (up to a point), providing more thrust but also leading to increased cavitation.

The 2-dimensional examples shown in Fig 2 and Fig 4 are idealized cases. The real operating environment for a propeller is complex, because the flow into (and out of) the propeller is not uniform.
An example ‘wake distribution’, which is the velocity of the fluid entering the area occupied by the propeller, is shown in Fig 5 for a single-screw vessel. In this image, the flow is symmetrical about the centreline (left side of the image) and the semi-circle denotes the area occupied by the propeller. The contour lines are boundaries of equal velocity; the values assigned to each contour are ‘wake fractions’, which are essentially an inverse of flow velocity. A wake fraction of 0.9 is equivalent to a flow velocity that is 10% of the vessel speed and a wake fraction of 0.1 is 90% of the vessel speed. The flow velocity presented to a propeller can vary widely with position.

![Figure 5: Example Wake Distribution into the Propeller [17].](image)

The vessel’s presence causes this non-uniform flow. From the perspective of a stationary observer watching the vessel move by, the ship’s hull pushes the water forward. At the hull, the water is moving at the same speed as the ship; farther from the hull, the water moves slower (or is undisturbed). From the perspective of the propeller which is moving at the same speed as the ship, the water near the hull (at the top of Fig 5) is moving more slowly compared to the water far from the hull (at the bottom of Fig 5).

As a result, the shape of the hull and the resulting wake distribution into the propeller is an important factor in propeller performance, both with respect to thrust and cavitation noise. Note that twin screw vessels tend to have more uniform wake fields since the obstructions upstream of the propeller are not as significant [16]. A completely uniform inflow is not a practical reality.

Part of the propeller designer’s job is to optimize the shape of the blade and angle of attack to provide the required thrust while minimizing cavitation. The non-uniformity of the flow into the propeller complicates this task, since the effective angle of attack changes with changing flow velocity at the propeller. The changing angle of attack vs. blade position around the hub then changes the suction pressures, thrust force, and cavitation. For this reason, all propeller designs are a compromise which have to account for the vessel-specific non-uniform flow into the propeller.

There are several tools available to the propeller designer to reduce noise in a non-uniform wake. These largely involve geometrical changes to the blade design, and include skew, pitch distributions, rake, warp, etc. [18]. For brevity, these factors will not be described here in detail.

The point to recognize here is that propellers are not ‘one size fits all’. It is certainly possible to put nearly any propeller on any vessel and obtain some degree of thrust to propel the ship (ignoring obvious clearance or fitting issues). Off-the-shelf propeller designs are often implemented on vessels, particularly work boats and other vessels produced in quantity, for reasons of economy. However, in doing so the propeller geometry will not be designed for the specific wake profile of the vessel, and noise levels will rise in nearly all cases.

Reducing noise requires an understanding of the wake produced by the vessel, and using the appropriate engineering tools to design a propeller geometry that is optimized for that wake. Tools such as Computational Fluid Dynamics can be used to create and optimize the hullform and propeller.
details, and a variety of other methods are available for optimizing propeller blade shapes. These
efforts can be followed by model testing to further validate and refine the design. Such efforts are
most economical when performed at the design stage, though they are possible to carry out after the
vessel has been built.

What degree of noise reduction can be gained by such efforts? The answer depends on the specific
noise goals and what the design would be without such efforts. If an off-the-shelf propeller is replaced
by an optimized design then reductions of 5-10+ dB are possible [20]. For vessels with propellers that
have been designed to optimize thrust, noise reductions are more difficult though 3+ dB reductions
are possible, depending on the specific design. Costs for the additional design efforts have been esti-
mated to range between $50-200k USD [19].

2.3 Vessel Speed

Vessel speed has a significant influence on underwater radiated noise. For example, it is shown in
[9] that a cruise vessel produces roughly 5 dB less noise when transiting at 7.2 knots vs 10.5 knots.
This effect is typical when the propeller is cavitating [17]. Furthermore, a ‘cavitation inception speed’
can be defined for any vessel, below which there is no cavitation and therefore no cavitation noise.

It is clear that operations at slower speeds can yield large reductions in noise. However, simply
slowing vessels down, as discussed in [3], may be operationally difficult. There is certainly a cost to
any vessel operator for moving more slowly through the water, and while this may be partially offset
by reduced fuel consumption it is a factor that needs to be considered if this approach is to be used.

2.4 Other Design Considerations

In general, larger diameter, slow turning propellers will produce less noise for the same thrust as
compared with smaller, higher speed propellers. Twin screw designs can also reduce noise relative to
single screw designs since two lightly loaded propellers are better for noise than one heavily loaded
propeller. Controllable pitch propellers (designs that allow the blades to change their angle of attack)
can have reduced noise relative to fixed pitch propellers, but only if the propeller speed is modified
along with pitch. Many Naval vessels use this approach to maintain reduced noise levels. While these
concepts can lead to reduced noise, they involve basic design decisions which need to be implemented
in the early design stages of a vessel [19].

Other propeller designs such as counter rotating propellers, ring propellers, rim drive propulsion
systems, and adding structures before or after the propeller to make the wake field more uniform can
also reduce cavitation noise [20]. Once again, these designs are best if implemented at the design
stage as retro-fitting vessels with these technologies would typically be expensive if not impractical.

One additional ‘technique’ that has been shown to have a significant impact on underwater noise
is regular maintenance. Fouled propellers will cavitate at lower vessel speeds / RPMs than a clean
propeller, and will therefore have increased noise. Regular maintenance and cleaning (as needed)
will help keep noise levels low [20].

3. Machinery Noise

Machinery induced underwater noise can range in level depending on the type of machinery, it’s
location in the vessel, and other factors. Vessels with propellers that are cavitating heavily will often
mask machinery induced noise, though low frequency tones from propulsion and power generation
equipment can be of similar level for some vessels. Machinery noise will be the dominant noise source
when propeller cavitation noise is low or non-existent.

All machinery items produce vibration and airborne noise within the machinery space. This noise
and vibration can travel along various paths, and will ultimately be radiated into the water as noise.
Details of these paths can be found in [19, 20]; their relative influences are a function of the sources
and structural details of the vessel. In general, larger machinery items that are located closer to the
waterline will cause more noise than smaller items located higher in the vessel [20].
The tools for assessing and reducing machinery noise exist today. Some of these tools have been implemented on vessels for decades, and improvements in technology both for treatments and predictions are continually being made. These tools include analytically and empirically based modelling software, such as that described in [21].

Common treatments for machinery noise include isolation mounting of machinery, application of insulation materials such as fiberglass and mineral wool (the same that are used for fire and thermal protection), and damping. Each of these treatments provides different acoustical effectiveness, depending on the dominant acoustical paths and the locations where they are applied. Additional details can be found in [19, 20].

In all cases, a detailed analysis must be performed in order to avoid over-treating the vessel, and to obtain the desired acoustical effectiveness. Such analyses can be performed at small cost relative to the cost of the vessel. Other non-acoustical factors such as weight and space must also be considered. Reductions on the order of 3-10+ dB are possible for many commercial vessels.

One additional method for reducing machinery noise is the selection of equipment with inherently low noise and vibration. This approach has minimal impact on space and weight, and cost increases may be relatively small to moderate. This is arguably the most effective approach to reducing noise, and can yield reductions on the order of 5-10 dB.

4. Conclusions

The arguments for reducing noise from vessels have been made, and regulatory bodies are listening. Various efforts have been undertaken to assess noise in the oceans caused by vessels (and other sources), along with attempts to correlate underwater noise to vessel size or other gross parameters. Such assessments of vessel noise are beneficial for understanding potential impacts from current shipping activities and for setting new objectives and noise limits. However, they cannot provide enough information to develop solutions for reducing noise on specific vessels, other than limiting vessel speed. For example, when inspecting Figure 1 by itself, one can only guess as to the cause of the peak seen in the cruise vessel noise data at 125 Hz. Without detailed design information of the vessel and appropriate analysis, the true cause of this peak remains unknown as are possible solutions.

The technology required to reduce noise from vessels is available today. Prediction, assessment, and design tools of various types have been developed over many decades, and are continuing to improve along with low noise design approaches and noise control materials. However, in order to be acoustically effective and economically viable, noise control solutions must be designed and implemented on a case-by-case basis.

The information required to identify effective noise control solutions cannot be determined from afar; real solutions can only be developed with an intimate knowledge of pertinent aspects of each vessel. Noise control is most effective when it is done at the vessel’s design stage. Retro-fitting treatments can be performed but it will typically lead to additional costs.

Vessels can be designed to be quiet. However, in order to make a significant impact there would need to be definitive noise goals for each new vessel that is constructed. Noise reductions are not free, but are possible for typical commercial vessels at an estimated additional cost of 1-5% of the total cost of designing and building a vessel without noise considerations. This estimate includes all engineering, procurement, and implementation costs, and assumes the noise goals equate to reductions on the order of 3-10 dB over existing noise levels.

REFERENCES

1 International Maritime Organization (IMO), Adoption of the Code on Noise Levels On Board Ships, Resolution MSC.337(91), Adopted on November 30, 2012.


