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# A REVIEW OF PRACTICAL METHODS FOR REDUCING UNDERWATER NOISE POLLUTION FROM LARGE COMMERCIAL VESSELS

R.C. Leaper, International Fund for Animal Welfare, UK and M.R. Renilson, Renilson Marine Consulting Pty Ltd, Australia.

SUMMARY
Underwater noise pollution from shipping is of considerable concern for marine life, particularly due to the potential for raised ambient noise levels in the 10-300Hz frequency range to mask biological sounds. There is widespread agreement that reducing shipping noise is both necessary and feasible, and the International Maritime Organization is actively working on the issue. The main source of noise is associated with propeller cavitation, and measures to improve propeller design and wake flow may also reduce noise. It is likely that the noisiest 10% of ships generate the majority of the noise impact, and it may be possible to quieten these vessels through measures that also improve efficiency. However, an extensive data set of full scale noise measurements of ships under operating conditions is required to fully understand how different factors relate to noise output and how noise reduction can be achieved alongside energy saving measures.

## 1. Introduction

Concerns that shipping noise could be affecting marine mammals were first raised in the 1970s, based on observations of considerable overlap between the main frequencies used by large baleen whales and the dominant components of noise from propeller driven ships [1]. Shipping noise also affects many species of fish causing avoidance behaviours [2,3], stress [4] and masking communication [5]. Increases in global shipping have been associated with documented increases in ocean ambient noise levels [6,7]. These increases amount to around 20dB from pre-industrial conditions to the present day in the northern hemisphere with deep water shipping noise up to 10dB higher than wind-related Knudsen noise at sea state 6 at frequencies below 100Hz [8]. In areas of highest shipping density, increases in noise can be much greater [9,10,11].

While there is still considerable uncertainty about the full impacts of noise on marine life, noise from shipping will mask sounds associated with communication, breeding and feeding for many species, with potentially serious consequences for individuals and at a population level. The primary concern regarding potential adverse impacts of incidental shipping noise is not related to acute exposures, but rather to the general increase in ambient noise [12]. The effects of acoustic masking have been quantified in terms of loss of acoustic habitat, with shipping noise in some cases contributing to an order of magnitude loss in the spatial area over which large baleen whales can communicate [11].

An International Workshop on Shipping Noise and Marine Mammals held in Hamburg in April 2008 [13] agreed as targets a reduction in the contribution of shipping to ambient noise levels in the 10-300Hz range of 3dB in 10 years and 10dB in 30 years, relative to current levels. These targets have been widely endorsed, including by the Scientific Committee of the International Whaling Commission [14].

In 2008, based on a proposal by the USA, the International Maritime Organization (IMO) added “Noise from commercial shipping and its adverse impact on marine life” as a high priority item to the work of its Marine Environment Protection Committee (MEPC) and established a correspondence group to develop non-mandatory technical guidelines for ship-quieting technologies as well as potential navigation and operational practices [15].

The European Union has adopted an indicator for Good Environment Status (GES) for underwater noise in the context of the Marine Strategy Framework Directive[1] based on trends in ambient noise levels within the 1/3 octave bands centred at 63 and 125 Hz. These bands are dominated by noise from ships, and achieving GES may require reductions in shipping noise. In the US, the National Oceanic and Atmospheric administration has held two symposia on vessel noise [16,17]. One conclusion was that substantial reductions (5-20dB) in noise emissions could be achieved for most types of vessel at relatively little cost without major technical innovation.

There is thus a wide agreement that reducing shipping noise is both necessary and feasible. The IMO correspondence group has been developing technical guidelines for how noise reductions may be achieved, bearing in mind the relatively little attention given to underwater radiated noise in ship design and construction to date. In particular, the group noted that quieting a relatively few of the loudest ships is a potential way to efficiently reduce the overall contribution of shipping noise to the global ocean noise budget [18].

[1] The European Marine Strategy Framework Directive (Directive 2008/56/EC) adopted in 2008 requires Member States to prepare national strategies to manage their seas to achieve or maintain Good Environment Status by 2020.

Although there are limited standardised noise measurements across merchant fleets, some quantitative estimates can be made of the likely effects of tackling a proportion of the noisiest ships based on simple assumptions about noise propagation. One study of measured noise from 54 vessels documented relative source levels expressed in dB across the 30–150Hz range [19]. Based on this distribution, vessels that are quieter than average contribute 10% or less to the total area ensonified by vessels to a specified received level. By contrast, the noisiest 10% of vessels (those that are 6.8dB or more above average) may contribute between 48% and 88% of the total acoustic footprint[2] [20]. For six cruise ships between 23 and 77GT, a standard deviation of 3.7dB in overall sound level was reported but up to 24dB differences between the quietest and noisiest in 1/3 octave band levels [21]. Similarly, 20-40dB differences in the upper and lower bounds of sound levels across an assemblage of 15 ships have been reported [22], demonstrating large differences in levels at certain frequencies.

In July 2011, the IMO introduced a mandatory Energy Efficiency Design Index (EEDI) for new ships which will require ship designers and builders to produce energy efficient ships [23]. At the same time, the Ship Energy Efficiency Management Plan (SEEMP) was made mandatory for all ships. The EEDI has been developed for the largest and most energy intensive sectors of the global merchant fleet, including tankers, bulk carriers, general cargo and container ships. The intention is to stimulate continued technical and design developments and to separate these from operational measures. The sectors of the fleet for which EEDI applies are also likely to include some of the noisiest vessels. Technological initiatives generated by EEDI and operational measures taken through SEEMPs could play an important role in reducing underwater ship noise. However, to achieve this, it is critical that the implications of all developments for noise are properly evaluated.

While the over-riding consideration of IMO remains on fuel efficiency and reducing $CO_2$ emissions, the noise issue should also be tackled at the same time. In this paper, potential methods for reducing ship noise that may also improve energy efficiency for both existing vessels and new builds are reviewed. In particular we identify the research needed to ensure that the opportunities for noise reduction arising from efficiency measures are not missed.

## 2. Background to underwater noise from ships

### *2.1 Principal cause of shipping-related hydro-acoustic noise*

There are a number of different causes of noise from shipping. These can be subdivided into those caused by the propeller, those caused by machinery and those caused by the movement of the hull through the water. The relative importance of these three different categories will depend, amongst other things, on the ship type. For a typical vessel, the ratio of energy emitted as noise to the energy used for propulsion is around $10^{-6}$ [24] with the amount of energy generated as noise typically a few hundred watts or less. Therefore small changes in propulsive efficiency can make dramatic differences to noise output.

It should be noted that until recently, there have been no standards for measuring and assessing hydro-acoustic noise propagated into the water. Measurements were made by different organisations using different techniques, with different methods of extrapolation to determine the source level. In December 2009, a new voluntary consensus standard for the measurement of underwater noise from ships was developed by the American National Standards Institute and the Acoustical Society of America (ANSI/ASA 2009). The standard describes measurement procedures and data analysis methods in order to quantify a ship's underwater radiated noise level referenced to a normalised distance of 1m. Three different standards (A,B,C) are specified according to the level of precision required.

The International Standards Organisation (ISO) has been developing a standard[3] in close co-operation with the group that developed the ANSI/ASA standards and expects this to be published in 2012. The standard has been developed at the request of the IMO, shipping and shipbuilding industries, who wished to have an easy-to-use and technically sound International Standard for measuring underwater noise radiated from merchant ships.

The noise from the propeller will depend on whether it is cavitating[4] or not. Noise from a cavitating propeller dominates other propeller noise, other than singing (see

[2] In this paper the term 'acoustic footprint' is used to denote the relative area over which the average, wideband sound from a ship will exceed a certain level under very simple and approximate assumptions about propagation. For the subsequent acoustic footprint comparisons in this paper, a spreading loss in dB of 15log($r$) where $r$ is the distance from the ship is assumed. For example, a 15dB increase in source level will result in the same received level at a factor of 10 greater range and an area of the acoustic footprint which is 100 times greater. This is a crude measure that does not take into account frequency characteristics of the noise or the complexities of propagation, but does provide a simple measure for comparative purposes.

[3] International Standard ISO 16554 Protecting marine ecosystem from underwater irradiated noise – Measurement and reporting of underwater noise radiating from merchant ships

[4] Cavitation occurs when the local pressure is lowered to the vapour pressure of the water.

2.3), and all other hydro-acoustic noise from a ship [25]. In view of this, the IMO correspondence group concentrated its attention on various aspects of vessel propulsion, followed by hull design, on-board machinery, and operational measures [18].

Generally, it is possible to avoid cavitation at low speeds, however at high speeds this is not possible. Surface warships, particularly those used for Anti-Submarine Warfare, are designed to operate as fast as possible without cavitation occurring. However propellers will inevitably cavitate above a certain speed, no matter how well the ship and propellers are designed. Considerable research has gone into making some military vessels, which are already very quiet, even quieter. However these technologies are unlikely to be appropriate for reducing the noise generated by the noisier merchant ships.

The lowest speed at which cavitation occurs is known as the Cavitation Inception Speed (CIS). The CIS for warships will typically be below 15 knots. There are published examples of research vessels using advanced propeller technology to improve CIS where the CIS is about 10 knots [26,27,28].

Warship designers try to ensure that cavitation does not occur at low operating speeds and hence other sources of noise become important. The same applies for specialised quiet vessels such as research vessels [29,30]. However, this is not the case for normal merchant ships. Thus, the noisiest merchant ships, which have not been designed to reduce cavitation, will experience cavitation. If the noise from one component is 10 dB above other components of noise, then the other components are largely irrelevant [31]. Cavitation certainly has the potential to generate noise that is greater than 10 dB above machinery and other noises [32]. Therefore, it is almost certain that cavitation noise will dominate the underwater noise signature of large commercial vessels and noise reduction methods should be directed at reducing cavitation noise [18].

### *2.2 Factors affecting cavitation performance*

For a given propeller blade design a greater blade area can produce a given thrust with a smaller difference in pressure between the face (pressure side) and the back (suction side) of the blade. Thus, an increased blade area will result in reduced cavitation. Unfortunately, increasing blade area increases the torque required to rotate the propeller. Hence, for merchant ships, greater efficiency is possible with lower blade area, and so a small amount of cavitation is associated with the optimum propeller design. Excessive cavitation, however, can reduce the thrust and also cause erosion, both on the propeller, and in some cases, on the rudder.

The other major contributor to the cavitation performance of a propeller is the flow into it. As the propeller rotates it will experience vastly varying inflow, known as wake, caused by the hull ahead of it. Typically, for a single screw propeller the axial velocity into the propeller at the top of the circle is much lower than the axial velocity at the bottom. In addition, there will be a tangential component of the flow into the propeller, which will be quite different at the top of the propeller disk compared to the bottom. This means that the angle of attack of the propeller blade will be constantly varying through the cycle and will not be at the optimum value. Although it is well known that non-uniform wake can have a major influence on the operation of the propeller, and on propulsive efficiency, the effect on hydro-acoustic noise generated by a cavitating propeller is not fully understood.

Variation in water flow into the propeller, combined with the lower static pressure (due to hydrostatic head) for a blade at the top of the cycle can often result in fluctuating cavitation, with cavitation occurring at the top, but not at the bottom of the cycle. In any case, the cavitation extent for each blade will vary throughout the cycle. This will affect the noise by providing a frequency component corresponding to the blade rate (and harmonics).

Ships designed to reduce cavitation will have well designed after bodies with as uniform a flow into the propeller as possible. This cannot be overstressed as a major factor influencing propeller cavitation performance.

### *2.3 Propeller singing*

In some cases propellers can generate very high pitched notes, known as singing, caused by the shedding frequency of the trailing edge vortices coinciding with the structural natural frequency of the trailing edge of the propeller [33]. Audible singing can occur from approximately 10 – 1,200 Hz, although it has been suggested that it can be as high as 12 kHz [34]. Fortunately singing is usually very easy to cure. The normal procedure is to cut a very small section obliquely from the trailing edge of the propeller blade, leaving the trailing edge flat, with sharp corners on both the face (pressure side) and the back (suction side). The resulting shape is often referred to as an anti-singing trailing edge.

### *2.4 Vessel load condition*

Propellers are generally designed for the full load condition. However, few ships spend all their time in this state. For a range of practical reasons, when in ballast a ship is never loaded close to its full load condition. Consequently, the propeller is much closer to the surface, and the tip of the propeller may be above the waterline. The lower pressure due to the smaller hydrostatic head is likely to cause be significantly more cavitation for a vessel in ballast than in full load.

In addition, when a ship is in ballast it is usually trimmed by the stern. This generally has a significant detrimental effect on the wake field to the propeller, further worsening its cavitation performance. Hence it is likely that a tanker or bulk carrier in ballast will generate more hydro-acoustic noise than one in full load.

### 2.5 Effect of speed

When ships are operating below CIS then the hydro-acoustic noise levels will be reduced considerably. However, this speed is likely to be around 10 knots, or lower, and for many merchant ships operation at such speeds is impracticable. Therefore, merchant ships will be exhibiting some level of cavitation, and so in this paper the effect of speed is only considered above CIS.

Although there is limited detailed information about the effect of speed on the hydro-acoustic noise generated by merchant ships, it is clear that in general for a ship fitted with a fixed pitch propeller, reducing the speed reduces the overall noise [21,32]. However, levels may not necessarily decrease across all frequency bands. Quantifying the relationship between speed and noise is complex and the limited data available do not always indicate a consistent relationship. A model giving generalised relative expected spectrum levels ($S$) in dB in terms of speed and length of the ship relative to a reference speed $V_0$ and reference length $L_0$ (equation 1) has been suggested [35]

$$S = S_0 + 60\log(V/V_0) + 20\log(L/L_0) \qquad (1)$$

One study found no relationship between speed and noise levels for assemblages of ships but noted that the relationship suggested in equation 1 may still hold for individual vessels measured at different speeds [19]. Comprehensive experiments conducted on a military coal carrier fitted with a fixed pitch propeller gave a significant linear relationship between the wideband source level ($Sw$) in dB and speed ($V$) [36]

$$S_w = 61.9\log(V) + 117.9 \qquad (2)$$

This would appear to be consistent with the relationship suggested in equation 1, at least for this one ship. Earlier measurements made on small craft also showed a linear relationship between the noise level in dB and the log of the speed [31].

In the absence of direct noise measurements, the relationship between speed and power can provide a qualitative indication of how noise output may be affected by changes that result in small increases in efficiency due to cavitation reduction for fixed pitch propellers. The situation is not so clear for ships fitted with controllable pitch propellers. Whilst results from tests on a cruise ship fitted with controllable pitch propellers generally shows an increase in noise with increasing speed [21], this is not always the case. In all cases full scale measurements are needed for quantitative analyses of the relationships between speed and noise.

## 3. Practical Technologies for Reducing Noise on Merchant Ships

### 3.1 General

There are a range of technologies that can be used to reduce the hydro-acoustic noise generated by ships. For example, warships and research vessels make use of specialised propellers which are designed to increase the CIS. Unfortunately, many of these noise reducing technologies result in propellers which are less efficient than the existing conventional propellers normally used in merchant ships. These noise reducing technologies will not be dealt with here, as their use would increase the carbon footprint of the vessel, increase the operating costs, and are unlikely to be embraced by commercial ship designers and owners. Instead, the noise reducing technologies reviewed are those which claim to increase the efficiency, and thereby reduce the running costs.

### 3.2 Propeller blade surface

Propeller blades are subject to impact damage and other defects during their lifetime. Small imperfections, particularly in the leading edge, can reduce the efficiency of a propeller by the order of 2%, depending on the damage [38] which should be repaired during routine dry dockings. In addition, a certain amount of polishing can be conducted afloat, which will ensure the propeller remains as efficient as possible. Imperfections can significantly effect local cavitation, resulting in increased hydro-acoustic noise. In addition, it has been shown that improving the general surface of a propeller from that typically specified for normal merchant ship use by applying a modern non-toxic antifouling system referred to as a Foul Release system can increase the efficiency for a medium sized tanker (100,000 dwt) by up to 6% [39,41]. There have been some reports that these coatings can also reduce the noise.

### 3.3 Optimised conventional propeller design

Propellers are designed for predicted operating conditions, which rarely occur in practice. Firstly, the design is often optimised for the full power condition, whereas it is likely in practice that the machinery will be typically be operated at 80 – 90% of the maximum continuous rating. Secondly, the propeller is designed for a predicted ship speed and wake distribution. Although these may have been obtained from model experiments, there will always be some uncertainty in model to full scale correlation, and so the actual operating condition will be different to that assumed in the design. Most propellers are designed for full load condition, in calm seas, whereas many ships operate at lighter draughts in a seaway.

Many shipping companies are now adopting 'slow steaming' philosophies, to reduce fuel consumption (see 3.9). This will also mean that the propeller has not been designed for the actual operating conditions.

### 3.4 Special merchant ship propellers

As discussed above, cavitation from the propeller is without doubt the most serious source of hydro-acoustic noise from large merchant ships. Therefore, the best way to reduce noise is to make use of a propeller specially designed to minimise cavitation.

Propellers designed to avoid cavitation altogether below a given speed are less efficient than a conventional merchant ship propeller, and hence are probably not likely to be applied routinely on commercial vessels. There are, however, some basic principles that can be applied to reducing the propeller noise without decreasing efficiency [25].

There are also a number of propriety propeller design concepts that claim increased efficiency and a reduction in cavitation/vibration. These include High Skew Propellers [25,42]; Contracted and loaded tip propellers [43,44], Kappel propellers [45] and New Blade Section (NBS) propellers [46]. Claims reported by the proponents of these concepts have yet to be independently verified. Also, although claims of reducing cavitation are made, it is not clear exactly how much these will reduce the hydro-acoustic noise. Most of the emphasis of the concepts has been to increase efficiency, and to reduce noise and vibration propagating into the ship.

It is important to recognise that there are many other concepts which claim to increase efficiency and to reduce noise and vibration, and that different approaches may suit different vessels. For all these designs of propeller, noise measurements are required to verify whether claimed improvements in efficiency are matched by reductions in noise.

### *3.5 Propeller hub caps*

A propeller generates vortices from its hub, which reduce its efficiency, and are prone to cavitate. The magnitude of these vortices will depend on the blade radial loading distribution, and on the size and design of the hub. Vortices from the hub tend to be steadier than those generated from the propeller tips, and consequently have an influence at the higher frequency range, rather than direct harmonics of the blade rate frequency.

Properly designed hub caps can reduce the hub vortex cavitation, and consequently the hydro-acoustic noise, as well as improving propeller efficiency, particularly for controllable pitch propellers [47]. Two concepts which can be used to reduce hub vortex cavitation are Propeller Boss Cap Fins [48, 49], and Propeller Cap Turbines.

### *3.6 Wake inflow devices*

Improving the wake into the propeller will reduce cavitation, and probably also increase efficiency. If the wake is already good flow modification devices are unlikely to improve the situation, however such ships are not likely to be amongst the noisiest, and hence not a priority for noise reduction.

There are a number of devices that can be fitted to the hull of a ship to improve the flow into the propeller including Schneekluth duct, Mewis duct, Simplified compensative nozzle and Grothues spoilers [42,48, 49,50,51].

### *3.7 Propeller/Rudder Interaction*

The interaction between the propeller and the rudder has a significant impact on propulsive efficiency. Various concepts such as a twisted rudder (better designed to account for the swirling flow from the propeller) and rudder fins (designed to recover some of the rotational energy) have been developed to increase efficiency [52].

In addition, the Costa Propulsion Bulb (CPB) is a concept where the propeller is integrated hydrodynamically with the rudder by fitting a bulb to the rudder in line with the propeller shaft. It is claimed that this can reduce the hydro-acoustic noise levels by 5 dB [25].

### *3.8 Changes to the hull form*

The hull form will have a considerable influence on the power required to propel the vessel, but also on the hydro-acoustic noise from its propeller. A well designed hull form will require less power for a given speed, which is likely to result in less noise. In addition, a well designed hull form will provide a more uniform inflow to the propeller, thereby increasing the propeller's efficiency, and reducing noise and vibration caused by the uneven wake flow. This will further reduce the underwater noise.

One special technique for improving the flow into the propeller of a single screw merchant ship is to adopt an asymmetrical afterbody. The flow around single screw ships is not symmetrical about the centreline, since the propeller tip is moving one way at the top of the propeller disk, and the other way at the bottom. The principal aim of the asymmetrical afterbody is to take this into account, and reduce the power required by improving the flow into the propeller. Claims of reduction in power of up to 9% have been made [53].

### *3.9 Changes to operating procedure*

The most general relationship between overall wide-band hydro-acoustic noise and ship speed for merchant ships with fixed pitch propellers travelling above CIS, seems to be that noise expressed in dB will increase according to *60log(speed)*. Although this relationship will not hold for all vessels, it does provide a useful indication of the likely reduction in acoustic footprint associated with reduced speed. In particular, although slower steaming will require more ships to be operated to carry the same quantities of cargo there should be a large reduction in total acoustic footprint associated with slow steaming. For example, the acoustic footprint for an individual ship at 12 knots would be 10% of that ship at 16 knots, but the number of ships required would increase by 33% for the same quantity of cargo carried. Thus the total acoustic footprint at 12 knots would be 13% of that for the same cargo transported at 16 knots. Similarly, the total acoustic footprint at 12 knots would be 34% of that at 14 knots. Compared to typical container ships travelling at 25 knots, total acoustic footprint would be reduced to 21% for slow steaming at 20 knots and 7% for extra slow steaming at 17 knots, allowing for the extra vessels required to transport the same cargo.

Where slow steaming is used, as noted above, it is particularly important to consider a redesign of the propeller(s), especially for ships fitted with controllable pitch propellers.

Noise from shipping that enters the deep sound channel will propagate more efficiently than noise in a homogenous water column and can contribute to raised ambient noise levels across an entire ocean basin. Noise generated at the surface may enter the deep sound channel where the sound channel intersects bathymetric features such as the continental slope or at high latitudes where it is very close to the surface [7]. Hence the contribution of shipping noise to ambient noise may be reduced by minimising the time spent in locations where sound will propagate into the deep sound channel. In some areas this may be achieved by transiting further off-shore, although the implications of any increase in distance travelled or increase in speed would need to be carefully considered.

## 4 Discussion

Although there are only limited data on the propagated hydro-acoustic noise for merchant ships, the large measured differences between the noisiest and quietest across merchant fleets indicates the potential to reduce the noise generated by the noisiest ships. Based on existing technology it is reasonable to be cautiously optimistic that the noisiest ships can be quietened without reducing their propulsive efficiency. The greatest improvements are likely to be achievable for ships operating at sub-optimal efficiency and these are also likely to be the noisiest.

It is almost certain that these noisiest ships suffer from greater cavitation than other merchant ships. For merchant ships it is necessary to accept a certain level of cavitation, as this gives a more efficient propeller than one designed to eliminate it altogether.

Reducing the noise generated by cavitation is not currently the main focus of the extremely quiet ships developed for military purposes as they concentrate on reducing the noise at speeds below CIS, and on raising the CIS as high as possible. Thus the technologies developed by the military cannot be directly transferred to merchant fleets. However, a number of technologies can improve efficiency and are likely to reduce hydro-acoustic noise.

The two critical aspects influencing cavitation performance are the propeller design itself, and the wake into the propeller, which is determined by the presence of the hull. Therefore, careful propeller and hull design are essential to improving the cavitation performance.

In addition, as ships often operate in different conditions to those predicted at the design stage, it is also likely that if the propeller were redesigned to suit the actual operating conditions this would result in an improved propulsive efficiency, as well as reduced hydro-acoustic noise.

There are a number of different propellers design concepts that have been developed in order to increase propulsive efficiency and/or reduce pressure pulses and associated hull vibration. In most cases, it is not known how these concepts will influence hydro-acoustic noise, however available data suggest noise is likely to be reduced. To most effectively address the noise problem, detailed measurements of noise associated with different propeller design concepts are needed.

There is also the potential to improve the wake flow into the propeller for existing ships by fitting appropriately designed appendages such as wake equalising ducts, vortex generators or spoilers. The technology exists to do this, and although there is some understanding of the improvement that these devices will have on propulsive efficiency, there is little knowledge about how they will reduce the hydro-acoustic noise. As with propeller designs that improve efficiency, it does seem very likely that improved wake flow will also reduce noise, but noise measurements are also required for these concepts. While some noise measurements may be made at model scale facilities, there is also likely to be a need for full scale measurements particularly at low frequencies where noise can be generated by vibration of rudders and other appendages.

For new ships, the wake flow can be improved by more careful design, which will require an increased design effort, including careful model testing and computational fluid dynamics analysis. For ships which spend time in ballast, this work should be extended to include optimisation of the propeller design and wake flow in that condition. This extra effort will cost more, however it is likely to result in improved propulsive efficiency as well as reduced hydro-acoustic noise.

The main challenge in ensuring that efficiency measures also optimise their potential for noise reduction is in moving from theoretical predictions and model tests to full scale at-sea measurements of noise from ships under typical operating conditions. The development of standards for such measurements by ISO and ANSI/ASA has highlighted some of the difficulties in obtaining sufficiently precise, comparable measurements. For example, even under calm conditions fundamental blade rate sound of a medium sized merchant vessel can exhibit a standard deviation of about 5 dB with most of the variations roughly correlating to the pitch period of the ship [36]. A 5dB difference corresponds to about a factor of 5 in acoustic footprint and is greater than the 3dB target reduction for overall shipping noise within 10 years, yet is difficult to reliably measure. Thus quite subtle differences in operating conditions may confound results. Reliable conclusions on the most effective noise reduction techniques will require extensive data sets.

Although model scale measurements cannot replace those made at sea, they could nevertheless give useful indications, and important insights would be gained if tank testing facilities adopted measurement of noise as a matter of routine. Despite the IMO recommendation in 2009 that member states should review their fleets to identify the noisiest vessels, the lack of sufficient measurements from ships at sea continues to hamper a full understanding of the most effective noise quieting methods.

## 5 Way ahead

While attempts to mitigate impacts of other noise sources such as sonar and seismic surveys on marine life have so far proven difficult and costly, substantial reductions in shipping noise appear technologically and economically feasible. There is increasing evidence that there are definite limits to the resilience of marine ecosystems [54], and this will apply to the introduction of noise from shipping. Although it may not be possible to determine how close to these limits some species or ecosystems have been pushed by elevated noise from shipping, the relatively small costs but potential benefits make addressing the ship noise problem a high priority.

Figure 1 outlines the possible activities required to reduce the noise propagated into the water by conventional merchant ships. Many of these could follow from efficiency initiatives related to the introduction of the EEDI. Central to most of these activities is the need for more measurements at both model and full scale, requiring the adoption of international standards for such measurements. The increased understanding that will then arise based on the results will input into theoretical models, and improved propeller and hull designs. In turn, noise measurements may also indicate energy efficiency issues that can be addressed within a vessel's SEEMP.

## 6 Concluding remarks

It appears that there is considerable difference in the noise propagated by the noisiest and the quietest conventional merchant ships (excluding those designed specifically for low noise).

It is reasonable to develop a cautious note of optimism that the noisiest ships can be quietened using existing technology without reducing their propulsive efficiency.

There is little doubt that the dominant feature of these noisiest merchant ships is cavitation associated with the propeller. The two major aspects that influence the level of cavitation are propeller design and wake flow into the propeller.

As ships often operate in different conditions to those predicted at the design stage, it is quite likely that if the propeller were redesigned to suit the actual operating conditions this would result in an improved propulsive efficiency, as well as reduced hydro-acoustic noise.
In addition, there are a number of different propeller design concepts that have been developed by various proponents, normally with the express purpose of increasing propulsive efficiency and/or of reducing pressure pulses and associated hull vibration.

There is the potential to improve the wake flow into the propeller for existing ships by fitting appropriately designed appendages such as wake equalising ducts, vortex generators or spoilers.

For new ships the wake flow can be improved by increased design effort, including careful model testing and computational fluid dynamics analysis. For ships which spend time in ballast, this work should include optimisation of the propeller design and wake flow in that condition.

The way ahead to reduce the noise propagated into the water by conventional merchant ships includes the need for more measurements at both model and full scale, requiring the adoption of international standards for full scale measurements. The increased understanding that will then arise based on the results from these measurements will be able to be fed into theoretical models, and improved propeller and hull designs.

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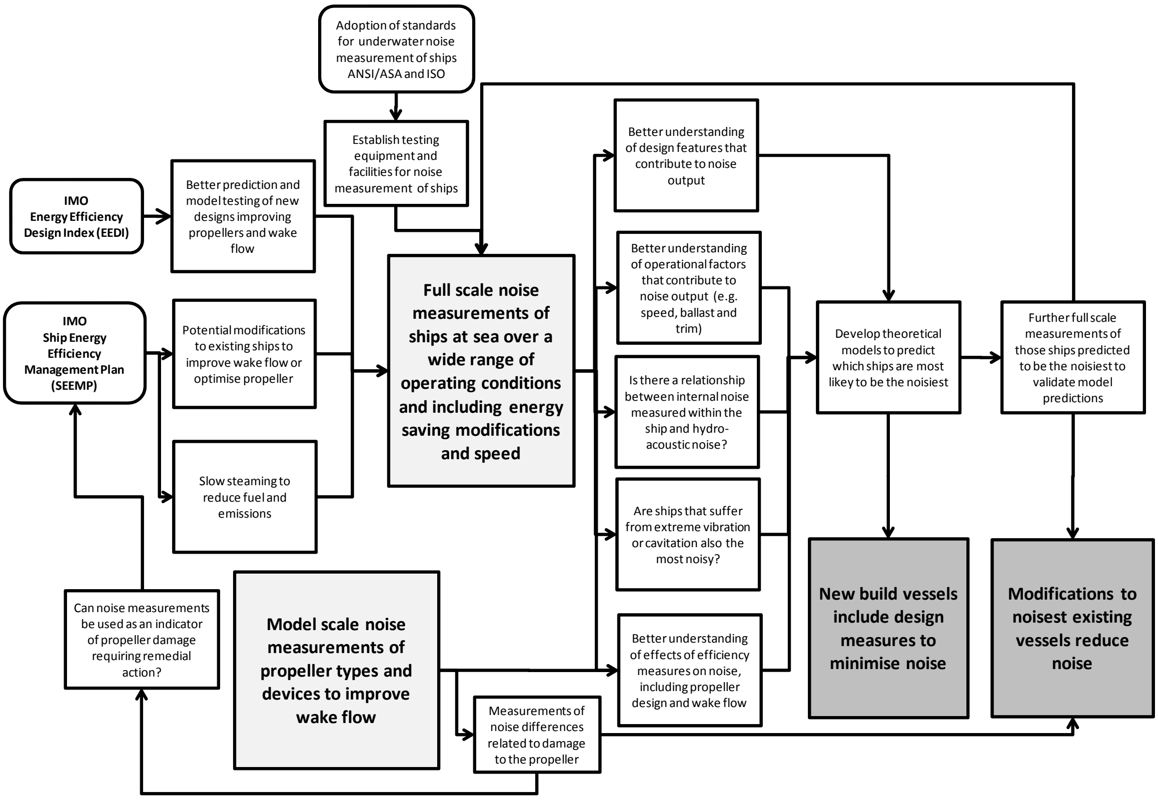


Figure 1. Flow chart of activities required to reduce the noise propagated into the water by conventional merchant ships. The central research requirement is for full scale noise measurements leading to a better understanding of the factors that cause noise and modifications to address these. Such modifications will be closely linked with measures taken to improve energy efficiency.