

## Hydro-acoustic noise from merchant ships – impacts and practical mitigation techniques

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### Abstract

The impacts on marine life of underwater noise pollution include disturbance, stress and the masking of biological sounds used to communicate and find food. Noise from shipping has resulted in elevated ambient noise levels in the 10-300Hz frequency range throughout the world's oceans, giving particular concern over impacts on marine mammals and especially large whales.

It has been shown that there is a difference in noise levels between the noisiest ones and the quietest ones of the order of 20 – 40 dB. This appears to imply that there is likely to be potential to reduce the noise generated by the noisiest ships.

Avoiding propeller cavitation altogether, and hence the underwater noise associated with this, can substantially reduce the noise pollution from a vessel. Technologies to suppress the onset of cavitation are used for military and specialist research vessels, however these are very specialised and often work at the expense of increasing the vessel's fuel consumption. Hence, such technologies are unlikely to be accepted by the broader commercial shipping community.

As the noisiest conventional merchant vessels are likely to suffer from excessive propeller cavitation, it is possible that a substantial reduction in the noise generated by these vessels can be achieved by reducing the extent of this cavitation. However the factors that contribute towards a ship being particularly noisy for its class are not well understood. We report a number of noise measurement studies of individual vessels and review a range of measures that may reduce underwater noise for the noisiest vessels in combination with improvements in fuel efficiency.

### 1. Introduction

The potential for shipping noise to negatively impact marine life and in particular, marine mammals and fish has received considerable attention in recent years. Such concerns were first raised in the 1970 for marine mammals (Payne &

Webb, 1971) but effects on many species of fish have also been demonstrated (Mitson & Knudsen, 2003, De Robertis & Wilson, 2010, Wysocki *et al.*, 2006, and Vasconcelos *et al.*, 2007).

Increases in ocean ambient noise levels which amount to around 20dB from pre-industrial conditions to the present day in the northern hemisphere (Andrew *et al.*, 2002, McDonald *et al.*, 2006, and Hilderbrand, 2009) can be explained by increases in the total number of ocean-going ships and their tonnage (Ainslie, 2011). In areas of highest shipping density, increases in noise can be much greater (Hatch *et al.*, 2008). Recent studies in localised areas have also related changes in ambient noise to changes in patterns of shipping. For example, McKenna *et al.* (2012) found a net reduction of 12 dB in ambient noise levels off the coast of Southern California between 2007 and 2010. They related this to a reduction in shipping and ships transiting more than 24 nm offshore to avoid restrictions on sulphur content in fuel. They predicted that a reduction of one ship transit per day resulted in a 1 dB decrease in average noise. Although average ambient noise is an important indicator of the overall effects of shipping it can be measured in several ways which are not always directly comparable (Erbe *et al.*, 2012; Merchant *et al.*, 2012).

The primary concern regarding potential adverse impacts of incidental shipping noise is related to the general increase in ambient noise rather than to acute exposure (IMO, 2008). Raised levels of ambient noise can result in masking of communication signals between animals (Clark *et al.*, 2009), changes in vocal behaviour (Melcón *et al.*, 2012; Ellison *et al.*, 2012), or reduced ability to find food. Shipping noise may also be associated with chronic stress in whales. Short-term reductions in shipping in the Bay of Fundy following the events of 11 September 2001, resulted in a 6 dB decrease in underwater noise and lower levels of stress hormones in whales within the Bay (Rolland *et al.*, 2011).

Although military technologies can be used to reduce noise levels generated by merchant vessels, these are expensive, and can reduce efficiency, thereby increasing fuel consumption. Consequently, they are extremely unlikely to be adopted by commercial ships.

However, it has been shown that there is considerable difference in the noise propagated by the noisiest and the quietest conventional merchant ships, and that the noise generated by the noisiest ones is due to excessive cavitation (Leaper & Renilson, 2012, and Renilson *et al.*, 2012).

Measurements taken by Wittekind (2009) showed that a small general cargo ship can be noisier than a containership 20 times the size and twice the speed. However, the combinations of factors that result in a ship generating 'noisy' cavitation and hence being excessively noisy are not well understood. The International Maritime Organization (IMO) has requested member states to review their merchant fleets to identify the noisiest vessels. There is also a need for further measurements of the underwater noise levels from individual vessels to understand better the role of factors such as loading, trim, vessel size and speed (Leaper & Renilson, 2012).

Technologies which reduce excessive cavitation can be expected to reduce the noise propagated by the noisiest ships, and hence to reduce the overall ambient noise levels in the oceans.

## 2. Key aspects of shipping noise

There are a number of different causes of noise from shipping. These can be subdivided into those caused by:

- i) the propeller(s);
- ii) the machinery (main engine(s) and auxiliaries); and
- iii) 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.

Noise from a cavitating propeller dominates other propeller noise, other than singing, and all other hydro-acoustic noise from a ship (Ligtelijn, 2007). Generally, it is possible to avoid cavitation at low speeds, however at high speeds this is not possible. Surface warships 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.

The lowest speed at which cavitation occurs is known as the Cavitation Inception Speed (CIS). Warship designers try to ensure that cavitation does not occur at low operating speeds and hence other sources of noise become important. However, this is not the case for normal merchant ships. Thus, the noisiest merchant ships will experience cavitation at their typical operating speeds.

If the noise from one component is 10 dB above other components of noise, then the other components are largely irrelevant (McCauley *et al.*, 1996). Cavitation certainly has the potential to generate noise that is greater than 10 dB above machinery and other noises (Wittekind, 2008). Therefore, cavitation noise will dominate the underwater noise signature of the noisiest large commercial vessels and so noise reduction methods should be directed at reducing cavitation noise.

## 3. Technologies for reducing noise

### 3.1. 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 (Townsin *et al.*, 1985).

Imperfections can significantly affect 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 of a medium sized tanker (100,000 dwt) by up to 6% (Atlar *et al.*, 2002; Mutton *et al.*, 2005) and hence it is expected that these coatings may also reduce the noise.

### 3.2. 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 and/or Computational Fluid Dynamics (CFD), 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 in reality many ships operate at lighter draughts and in a seaway.

Many shipping companies are now adopting 'slow steaming' philosophies, to reduce fuel consumption. This will also mean that the propeller has not been designed for the actual operating conditions. This is of particular importance for controllable pitch propellers, where the thrust has been changed by modifying pitch, whilst retaining the same RPM.

### ***Special merchant ship propellers***

As cavitation from the propeller is the most serious source of hydro-acoustic noise from large merchant ships the best way to reduce noise is to make use of a propeller specially designed to minimise cavitation and there are some basic principles that can be applied to reducing the propeller noise without decreasing efficiency (Ligtelijn, 2010).

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; Contracted and Loaded Tip (CLT) propellers, Kappel propellers; and New Blade Section (NBS) propellers.

In addition, tip rake can be used to improve cavitation performance. Tip rake towards the face can improve the cavitation performance (Ligtelijn, 2010).

#### ***3.3. 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.

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 (Gaggero & Brizzolara, 2011). Two concepts which can be used to reduce hub vortex cavitation are Propeller Cap Turbines and Propeller Boss Cap Fins (PBCF) (Ouchi *et al.*, 1991; Abdel-Maksound *et al.*, 2004; Mewis & Hollenbach, 2006). It is claimed that a PBCF can reduce the sound pressure level by 3 to 6 dB. This is thought to be due to the reduction in hub vortex cavitation.

#### ***3.4. 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 (Molland & Turnock, 2007).

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. In addition to eliminating the hub vortex this concept permits increased loading at the inner radii. It is claimed that this can reduce the hydro-acoustic noise levels by 5 dB (Ligtelijn, 2007).

#### ***3.5. 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 and it is considered well worthwhile investigating the use of such devices for the noisiest ships to both reduce propagated noise levels and also potentially improve propulsive efficiency.

### **4. Other issues**

#### ***4.1. Slow steaming***

When ships are operating below CIS 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 here 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 given ship fitted with a fixed pitch propeller, reducing the speed reduces the overall noise (Kipple, 2002; Wittekind, 2008). However, levels may not necessarily decrease across all frequency bands.

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. If the thrust is varied by varying pitch, and keeping RPM constant, then when operating at lower speeds many locations on

the propeller will be at a non-optimum pitch, resulting in poor efficiency and increased noise. In some cases back cavitation can occur over part of the blade, resulting in excessive noise.

Thus, slow steaming may not be the solution to reducing ship generated noise for all vessel types.

#### **4.2. Load condition**

Propellers are generally designed for the full load condition. However, few ships spend all their time in this state. In ballast, a ship is not loaded close to its full load condition and the propeller is much closer to the surface, so the tip of the propeller may be above the waterline. The lower pressure due to the smaller hydrostatic head is likely to cause 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. However, it is possible that this effect will be countered by propagation effects. An unloaded ship with a shallower propeller depth will decrease the effect of the dipole, thereby decreasing the amount of radiated sound from the ship in the horizontal direction (McKenna *et al.*, 2012).

### **5. Noise measurements**

Several recent studies have made noise measurements from individual ships. There are different approaches for doing this from dedicated noise measurement facilities using multiple hydrophones (Arveson & Vendittis, 2000), single or vertical arrays of hydrophones deployed from research vessels (Allen *et al.*, 2012; MCR, 2011) or autonomous recording packages on the sea bed. Some of these packages have been deployed for other research purposes but have been used

opportunistically to measure ship noise in combination with tracks of known vessels from AIS data (McKenna *et al.*, 2012).

McKenna *et al.*, (2012) measured radiated noise levels from 29 vessels and divided these into seven categories according to ship type. The frequency characteristics of the noise showed some common characteristics according to ship type. Bulk carrier noise was predominantly near 100 Hz while container ship and tanker noise was predominantly below 40 Hz. On average, container ships and bulk carriers had the highest estimated broadband source levels with container ships travelling faster but bulk carriers being larger. Across all the vessel types with size ranging from 11,000 – 61,000 GT and speeds ranging from 9 – 22 knots the standard deviation of the estimated source level in dB was 2.9. Within ship categories there was less variability. For example, for six container ships of very similar size (53,100 – 54,600 GT) travelling at similar speeds (20.6 – 21.8 knots) the standard deviation of the estimated source level in dB was 1.5. This study showed much less variability in broadband source levels than other studies (Wales and Heitmeyer, 2002; Carlton and Dabbs, 2009) although much depends on the frequency bands chosen and the method used for averaging (Figure 1).

Allen *et al.* (2012) found a 7dB difference in broadband source levels between two cruise ships of the same size built by the same yard using the same propulsion system and a 23dB difference across a sample of four cruise ships. Although relationships between speed and noise levels are not always apparent across different ship types, many studies have demonstrated increasing noise with speed for individual vessels or vessels of a similar class. Allen *et al.* (2012) reported measurements for 11 different fishing vessels showing a significant relationship with broadband source level (dB re  $1\mu\text{Pa}^2$ ) proportional to  $45\log(\text{speed})$ .

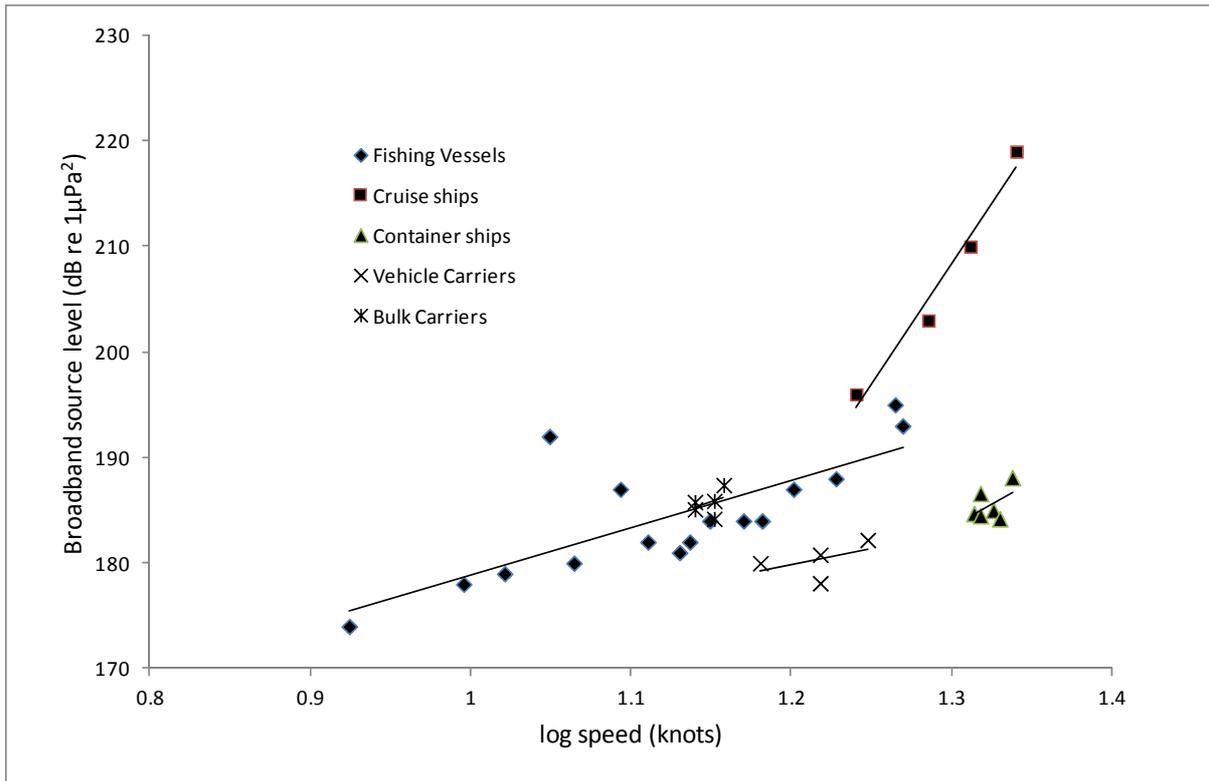


Figure 1. Broadband source levels against  $\log_{10}$  (speed in knots) for different ship types from two studies. Data on fishing vessels and cruise ships from Allen *et al.* (2012); data on other ship types from McKenna *et al.* (2012). Absolute levels from the two studies are not directly comparable but illustrate the relationships between speed and noise level.

Across a range of 27 vessels measured in the Channel (MCR, 2011), Renilson *et al.* (2012) found no significant relationship between noise and speed but draught aft was a significant factor with noise increasing with increased draught.

Two committees of the International Organization for Standardization (ISO) are currently working on standards that are relevant to underwater shipping noise. These are the new sub-committee on standards for underwater acoustics (ISO TC43, sub-committee 3 (SC3)) and technical committee on Shipping and Maritime Technology (ISO TC8).

A standard for ship noise measurement is being developed by TC8 with a draft standard ISO DIS 16554 “Ships and marine technology – Protecting marine ecosystem from underwater radiated noise – Measurement and reporting of underwater sound radiated from merchant ships”. These address a lack of internationally accepted standards for the terminology used to describe underwater noise and build on a previous ANSI S12.64 standard for ship noise measurement in deep water (Van der Graaf, 2012).

## 6. Concluding comments

It seems likely that with an appropriate research effort, many of the techniques being developed to improve fuel efficiency for large merchant vessels can also be optimised for noise reduction. The level of noise reduction for individual vessels needed to meet a widely endorsed international target of a 3 dB reduction in the contribution of shipping to ambient noise levels in the 10-300 Hz range over ten years (Wright, 2008; IWC, 2009), appears both practicable and economically feasible.

The study in the Bay of Fundy showed that a 6 dB reduction in noise from shipping resulted in a measurable decrease in indicators of stress in whales. This demonstrates that the type of measures discussed in this paper could make a significant contribution to reducing environmental impacts of shipping.

The IMO is expected to finalise guidelines for minimising noise from large commercial ships in 2013. However this is still an evolving issue and it is likely that advice to ship builders and operators on ways of reducing underwater noise will continue to develop. The European Union has recently funded two major projects related to ship noise. The SONIC (Suppression Of underwater Noise Induced by Cavitation) project aims to develop mitigation measures to reduce the noise footprint of

ships without reducing the fuel efficiency of the ships and also to develop design guidelines and tools for the development phase of the ship in order to reduce the noise footprint of new ships. The AQUO project (Achieve Quieter Oceans) aims to reduce the noise footprint from shipping. In addition to these projects there are many other opportunities for ship design and research test facilities to contribute to progress on the issue.

There still remains a need to measure noise associated with fuel efficiency measures and for full scale measurements of individual vessels. Recent studies have added considerably to the data available on individual vessels but also highlight some of the difficulties of obtaining consistent noise measurements given the potential for propagation conditions to cause variability of a similar magnitude to the differences between vessels that are attempted to be measured (Renilson *et al.*, 2012).

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