Renilson Marine Consulting Pty Ltd

REDUCING UNDERWATER NOISE POLLUTION FROM LARGE COMMERCIAL VESSELS

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Commissioned by

The International Fund for Animal Welfare

Summary

There is increasing concern about the effects of underwater noise on marine life. A major contributor to this is the noise generated by shipping.

The International Fund for Animal Welfare (IFAW) has identified that significant reductions in ambient noise can be made by reducing the noise output from the noisiest vessels. Resulting from this, IFAW commissioned Renilson Marine Consulting Pty Ltd (RMC) to undertake a brief desk top study into technologies that may be used to reduce the underwater noise output from the loudest commercial vessels.

This report is the primary output of the study, and is intended to inform discussions of technical measures and future research needs that can be implemented by governments and industry.

The report is arranged in four parts. Part I is the introduction and background, where some of the general issues are discussed. Part II covers some of the possible technologies that can be used to reduce noise for merchant ships, and Part III gives some examples for different ship types, discussing the practicalities and likely costs involved. Part IV is the recommendations and concluding comments.

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). Based on the current desk top study 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:

1. propeller design; and
2. wake flow into the propeller.

Improvements in propeller design, either by modifying the existing propellers, or by fitting new propellers designed with noise reduction in mind, have the potential to reduce hydro-acoustic noise for the noisiest merchant ships, and increase propulsive efficiency.

In addition, 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. 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 – however available data suggests that they will do so.

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 on the basis of the data available it is likely to result in improved propulsive efficiency as well as in reduced hydro-acoustic noise.

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PART I – Introduction and Background

1. Introduction

There is increasing concern about the effects of underwater noise on marine life. A major contributor to this is the noise generated by shipping. The International Fund for Animal Welfare (IFAW) has identified that a reduction in hydro acoustic noise of 3 dB for vessels which exceed mean noise levels of 175 dB by one standard deviation (16% of vessels) would result in a reduction of 40% in the area ensonified to 120 dB (assuming a standard deviation of 5.3 dB for assemblages of vessels as found by Scrimger and Heitmeyer (1981)). It also identified that a 6 dB reduction would reduce the corresponding area by 60%. Therefore, great gains can be made by reducing the noise output from the noisiest vessels.

Resulting from this, IFAW commissioned Renilson Marine Consulting Pty Ltd (RMC) to undertake a brief desk top study into technologies that may be used to reduce the underwater noise output from the loudest commercial vessels.

The objectives of the study were:

1. To examine the range of possible technologies that might be used to reduce underwater noise output from the loudest commercial vessels for new design and build.

2. To examine the range of possible technologies that might be used to reduce underwater noise output from the loudest commercial vessels during operation of current vessels.

3. To consider design or operational factors that might lead to particularly high noise output.

4. To review the likely implication in terms of initial cost, operating costs, effect on vessel handling and fuel efficiency for each identified technology.

5. To identify the most promising options for commercial vessels in terms of trade off between achieved noise reduction and overall costs.

This report is the primary output of the study, and is intended to inform discussions of technical measures and future research needs that can be implemented by governments and industry.

The report is arranged in four parts. Part I is the introduction and background, where some of the general issues are discussed. Part II covers some of the possible technologies that can be used to reduce noise for merchant ships, and Part III gives some examples for different ship types, discussing the practicalities and likely costs involved. Part IV is the discussion, concluding comments and recommendations for future research needs.

2. Background

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.

It should be noted that there is no standard way of measuring and assessing hydro-acoustic noise propagated into the water. Measurements are made by different organisations using different techniques, and different methods of extrapolation to determine the source level 1 m from the hull. See for example: Leaper and Scheidat (1998), McCauley *et al* (1996), and Wittekind (2008).

It is therefore recommended that a standard method of conducting and analysing full scale noise measurements be developed. This should take into account new technologies for recording hydro-acoustic noise, and the need for the measurement equipment to be portable. It should also make use of input from those experienced in conducting noise ranging for the military.

The noise from the propeller will depend on whether it is cavitating[1], or not. Cavitation noise dominates other propeller noise, other than singing (see below), and in fact all other hydro-acoustic noise from a ship when it is occurring (Ligtelijn, 2007).

Generally at low speeds it is possible to avoid cavitation, 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 inevitably the propellers will cavitate above a certain speed, no matter how well the ship and propellers are designed. Considerable research has gone into making such vessels, which are already very quiet, even quieter – however this technology is unlikely to make any significant difference to 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 value for any particular warship is classified, however it will typically occur below 15 knots. There are published examples of research vessels using advanced propeller technology to improve CIS where the CIS is about 10 knots (Atlar, *et al*¸ 2001, ter Riet *et al*, 2003, van Terwisga *et al*, 2004).

Warship designers go to great care to ensure that cavitation does not occur at low operating speeds and hence the other sources of noise become important. The same applies for specialised quiet vessels such as research vessels. (Ojak, 1988, and Brännström, 1995).

However, this is not the case for normal merchant ships (Ring-Nielsen, undated). Thus, there is no doubt that the noisiest merchant ships, which have not been designed to reduce cavitation, will experience cavitation. If the noise from one component of noise is 10 dB above other components of noise, then the other components are irrelevant (McCauley, *et al*, 1996). Cavitation certainly has the potential to generate noise that is greater than 10 dB above machinery and other noises (Witterkind, 2008).

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

As shown in figure 2.1, taken from Carlton and Dabbs (2009) existing merchant ships exhibit noise ranges which differ by as much as 40 dB from the upper bound of ships to the lower bound. This implies that there is at least the potential to reduce the noise level of the noisiest ships substantially.

Wittekind (2008) has also recently conducted a number of noise measurements on merchant ships, and showed a similar range to that given in figure 2.1. His work also demonstrated that the noisiest ships show signs of cavitation noise, and he too concluded that reducing this component of noise has the potential benefits in terms of reducing the noise generated by the noisiest ships, noting that it ought to be possible to reduce cavitation levels by about 10 dB, with greater improvements being possible with further research.

Thus, it is almost certain that cavitation noise will dominate the underwater noise signature of large commercial vessels, and for this reason the rest of this report will focus on ways to reduce cavitation on these ships.

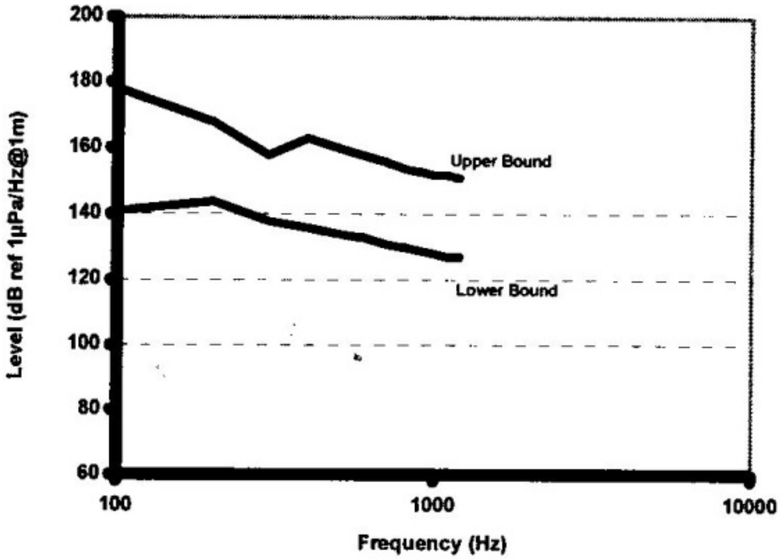

Figure 2.1 Bounds of noise spectra (15 ships)
(Taken from Carlton and Dabbs, 2009, with permission)

Unfortunately it is not possible at this stage to determine in advance which ships are most likely to be the noisiest ones without making hydro-acoustic measurements. It is therefore recommended that a study into the noise of various large commercial ships be undertaken in order to develop guidelines to help to identify the potential noisiest ones.

At this stage, in the absence of detailed information, it is generally assumed that a ship which experiences excessive internal noise and vibration is more likely to generate greater hydro-acoustic noise than one which does not. Although this is probably a reasonable working assumption, it is important to determine whether there is such a link. It is therefore recommended that a study into the relationship between internal noise and the level of noise propagated into the water be undertaken.

2.2 Factors affecting cavitation performance

As cavitation occurs when the pressure is reduced below vapour pressure, for a given propeller blade design, and a given thrust, the extent of cavitation is roughly related to the blade area, with an increased area resulting in reduced cavitation. This is because a greater blade area can produce the required thrust without the need for an extreme difference in pressure between the face (pressure side) and the back (suction side) of the blade.

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. This must not be excessive, however, as when the level of cavitation is increased it can reduce the thrust, and can also cause erosion, both on the propeller, and in some cases, on the rudder. Standard empirical methods are available, such as the Burrill Chart (Burrill and Emerson, 1978, reproduced in Carlton, 2007) which can be used to estimate the required blade area as a function of thrust (or power) for a given area of cavitation.

The other major contributor to the cavitation performance of a propeller is the flow into it. As the propeller rotates at the stern of the ship 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 of this on hydro-acoustic noise generated by a cavitating propeller is not fully understood. It is therefore recommended that this be investigated.

A typical example of an axial wake diagram for a single screw ship is given in figure 2.2, courtesy of Stone Marine Propulsion Ltd. The lines of contours represent the ratio between the ship speed, and the flow velocity at the propeller disk (without a propeller present). As can be seen the axial flow velocity reduces to as little as 20% of the ship speed. More importantly, the flow velocity is reduced to 30 – 40% of the ship speed over a large range of the top of the propeller disk, but is about 80 – 90% of the ship speed for a corresponding radius over the bottom of the disk.

This flow of water 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 component corresponding to the blade rate (and harmonics).

Thus, ships designed to reduce cavitation occurring will have well designed after bodies, with as uniform a flow into the propeller as possible. This is very important, and cannot be overstressed as a major factor influencing propeller cavitation performance.

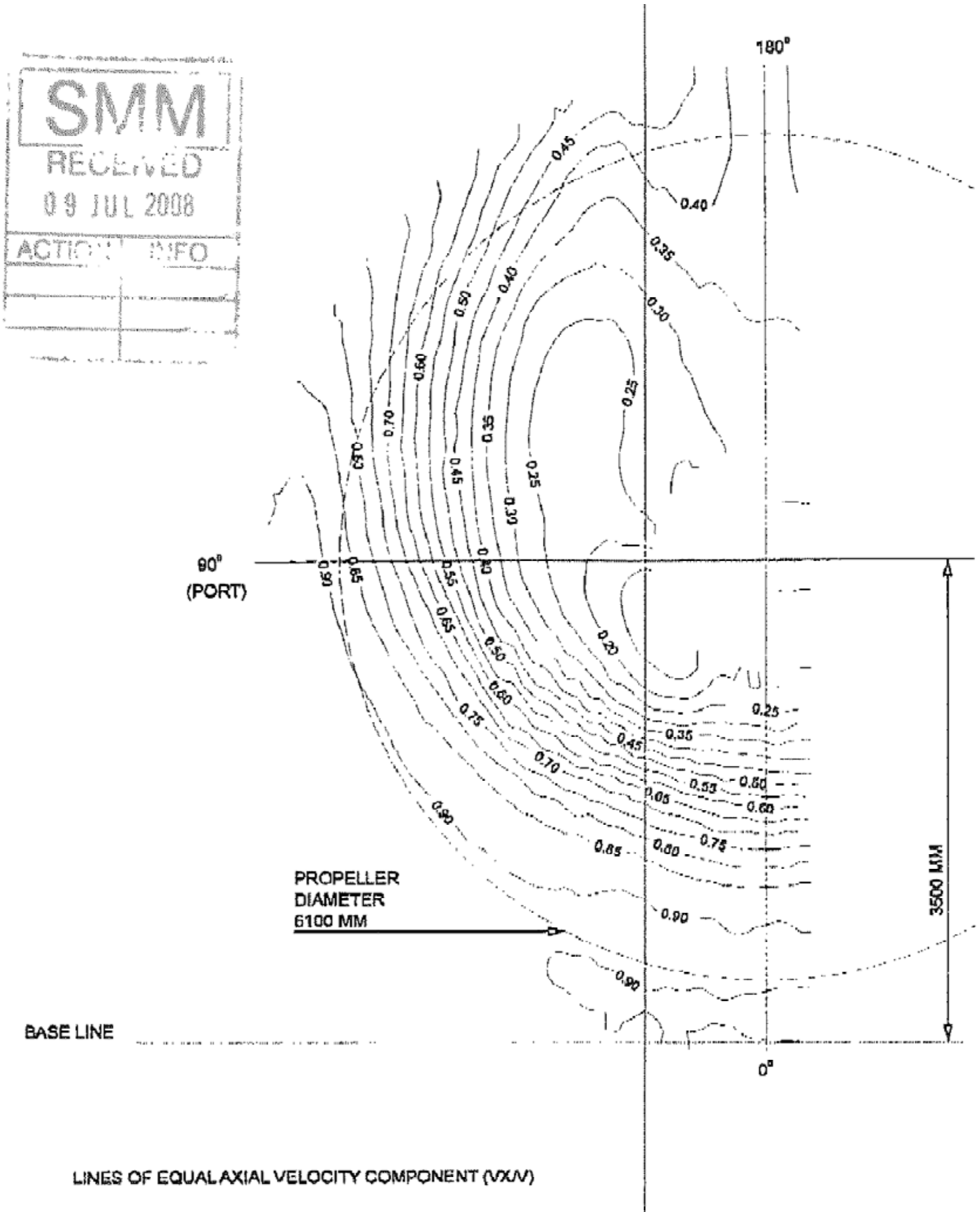

Figure 2.2 Typical wake diagram for single screw merchant ship
(Courtesy of Stone Marine Propulsion Ltd)

2.3 Cavitation assessment

The cavitation performance of a propeller cannot be assessed at model scale in a conventional towing tank because cavitation occurs when the local pressure has been reduced to the vapour pressure of water. Scaling this properly means that the atmospheric pressure above the water surface would need to be reduced at model scale. Although there is one such facility in the world, at MARIN, in the Netherlands, this is clearly very expensive, and not a common approach. Instead, most of the propeller testing that is conducted makes use of a cavitation tunnel, where the water is circulated in the vertical plane, with the test section at the top of the loop. The pressure in the tunnel can be reduced to enable the correct scaled cavitation number.

The larger cavitation tunnels are big enough to fit a truncated hull model in front of the propeller to correctly simulate the wake flow, which as discussed in Section 2.2 is of critical importance to the propeller performance. The wake is obtained using a grid arrangement in the smaller cavitation tunnels.

There are many such facilities around the world, however the majority of them are not ideal for measuring hydro-acoustic noise. Most military hydrodynamic establishments have specialised cavitation tunnels designed with as small a background noise as possible, with the express purpose of measuring noise. However, as the noise generated by merchant ships is much greater than that generated by warships it is possible in some cases to use a conventional tunnel to make useful measurements. See, for example, Atlar *et al* (2001). It is recommended that more noise measurements on commercial propeller designs be made in cavitation tunnels and correlated with full scale measurements.

When propellers are tested for cavitation performance in a cavitation tunnel the usual procedure is to observe the extent of the cavitation on both faces of the propeller blade, and record these by using either sketches or photographs. These records will typically be made for a range of propeller positions around the propeller disk. As noted above, the cavitation extent varies, with cavitation generally being greatest when the blade is at the top of the disk.

It is important to recognise that there are different forms of cavitation on a propeller blade, with different characteristics: sheet cavitation; bubble cavitation; cloud cavitation; tip vortex cavitation; and hub vortex cavitation. The first three of these cavitation types can occur on the back (suction side) or the face (pressure side). These are described well in many text books on the subject – see for example Carlton (2007), or Breslin and Anderson (1994).

As the main reason to avoid cavitation on large merchant ships is to prevent cavitation erosion on the propeller or rudder, it is this aspect of cavitation that designers tend to focus on. Currently a lot of research is being conducted in this field, however to date it is not possible to categorically state whether a particular form of cavitation will cause erosion, or not (Bark *et al*, 2004, and Carlton, 2009).

Until the recent past, it was generally thought that face cavitation was more erosive than back cavitation, and hence propellers tended to be designed with a large margin against face cavitation. Recent improvements in understanding have suggested that this may not be the case, leaving room to improve propeller blade design. Research is ongoing, as there is a considerable lack of understanding of the different types of cavitation and the effect of these on erosion and noise. It is recommended that this be pursued further, particularly for large merchant ships.

It is also worth noting that according to Carton (2009) only *'..some 5% or so of newbuild projects have the benefit of resistance and propulsion and propeller cavitation model testing during their design and construction phases.'* Thus, it is hardly surprising that many merchant ships end up with far greater noise levels (as well as possibly greater vibrations and lower efficiency) than would be possible with an optimised design.

2.4 Propeller singing

In some cases propellers can generate very high pitched notes, known as propeller singing. This is caused by the shedding frequency of the trailing edge vortices coinciding with the structural natural frequency of the trailing edge of the propeller (Carlton 2007). Audible singing can occur from approximately 10 – 1,200 Hz, although it has been suggested that this could be as high as 12 kHz (HyroComp, 2005).

Generally when singing occurs it does so over a limited range of propeller rpm. However, it can be so severe that it propagates into the vessel, and can cause annoyance to those on board the vessel.

Propeller singing has no known adverse effect, other than the noise generated, and as such it is possible that some owners may not even be aware that it is occurring. As any effects on propeller efficiency are negligible, there are no incentives for owners to fix a singing propeller, unless the noise transmitted into the ship is unacceptable to the crew.

Prediction of whether singing will occur, or not, is very difficult at the design stage, and there is at least one (classified) case of a warship propeller which exhibited singing.

Fortunately, however, 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.

Clearly, care needs to be taken to ensure that the resulting trailing edge is not too thin, however this procedure will normally cure the problem, and can easily be undertaken during a routine dry dock (Carlton 2007).

2.5 Manoeuvring and harbour performance

When ships are manoeuvring their propellers will be operating well away from the design condition, and it is possible that the noise generated due to cavitation will be excessive. However, this is not in the scope of the present study, and is therefore not considered further here.

2.6 Vessel load condition

Propellers are generally designed for the full load condition. However, few ships spend all their time at the full load condition.

Bulk carriers and tankers typically travel from the loading port to the destination port in full load, and then back again empty. As most of the mass of a loaded ship is the cargo, or deadweight, when a ship is empty it can be floating very high in the water, with minimal draught. This would cause problems with steering, propulsion, and slamming in a seaway. As a consequence ships are provided with the ability to take on sea water as ballast, to partly compensate for this.

However, for a range of practical reasons the ship is never really loaded close to its full load condition when in ballast. Consequently, the propeller is much closer to the surface, and in fact the tip of the propeller will often be above the waterline. As cavitation is dependent on the actual pressure on the blade, and as this will be lower due to the smaller hydrostatic head, cavitation is likely to be significantly worse 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.

The combination of being closer to the surface, and the poor wake field, both tend to counteract any possible advantages of the propeller being lighter loaded due to the ship being in ballast. This is not particularly well understood at present, and it is recommended that this be investigated further.

If the tip of the propeller is above the water surface the propeller will behave somewhat like a surface piercing propeller. This will generate ventilation[2], and increased noise. There is little data available regarding the noise generated from a surface piercing propeller, however it is known anecdotally to be noisy (although this is probably more to do with airborne noise than waterborne noise). It is recommended that this is investigated further.

Hence it is likely that a tanker or bulk carrier in ballast will generate more hydro-acoustic noise than one in full load. This has been shown to be the case in the limited data available at model scale (Mutton *et al*, 2006*)* and at full scale (Wittekind, 2008).

Unfortunately, the ability to install additional ballast is limited. As oil and most dry bulk cargoes have densities close to seawater they occupy most of the space within a large tanker or bulk carrier when loaded. This leaves little additional space for ballast when the ship is unloaded. The alternative of making use of cargo space for ballast when it is empty is difficult, and has been banned for tankers due to the problems associated with mixing of residual cargo oil with ballast water.

Further constraints are the need to achieve adequate draught at the bow to prevent slamming in a seaway, and the need to distribute the ballast over the ship length to prevent excess loading on the hull girder. Poor loading has been known to cause at least one bulk carrier to break in half!

In addition to the two extremes of full load and ballast, many ships operate at part load. For many ships, including bulk carriers, this could be due to the need to restrict the draught to use a particular port, and for others, such as containerships, this may simply be because the ship has been filled with cargo of lower density, and hence it is not down to its marks. It is unknown what effect these smaller changes in draught have on the hydro-acoustic noise generated.

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[2] Ventilation is caused when air is drawn into the water from the free surface, whereas cavitation is caused by the pressure being lowered to vapour pressure locally.

2.7 Propulsion configuration

There are a range of different propulsion options for large conventional merchant ships.

Propeller types

Two different types of propeller are used: a fixed pitch (FP) or a controllable pitch (CP). Fixed pitch is more common on large merchant ships, and is generally considered to be the more efficient option. With a fixed pitch propeller (FPP) the ship speed is varied by varying the propeller rpm, and reverse is obtained by reversing the direction of rotation of the propeller. With a direct drive to a slow speed diesel engine this means that reverse is only obtained by reversing the direction of the engine. Also, the engine must be stopped to give zero thrust. This takes time, and can make manoeuvring at low speed difficult.

With a controllable pitch propeller (CPP) the ship speed is varied by a combination of varying propeller rpm and varying pitch. This combination is preset as part of the control mechanism. Usually, what this means is that for higher speeds the speed control is achieved by varying pitch, however for the lower speeds the rpm is reduced also. For reverse the engine direction remains the same, and the pitch is put into reverse. This is a lot quicker than stopping the engine, and restarting in reverse, as required by a FPP, and hence low speed manoeuvring and berthing is a lot easier. For this reason, ferries and other vessels that berth a lot often use CPP.

As the CPP system means that the shaft is always turning it is easier to use this to take power for auxiliaries and hotel loads[3], which is another advantage of the CPP. However, the CPP requires a larger hub diameter, and this can have noise implications with regard to hub vortex cavitation.

One very important aspect to realise is that the CPP changes the angle of the blades, and hence for pitch values other than the design pitch only the position at one radius will actually have the ‘correct’ pitch. This means that when slow steaming the pitch will not be correct for most of the blade (too high in the outer radii and too low in the inner radii*)*. The result will be poor efficiency, and excessive cavitation, with the resulting increased noise. Berghult (2000) gives some experimental results which demonstrate this very well, with the tip vortex cavitation noise reducing by 15 dB for the 50% load condition compared to the 100% condition when the pitch was kept constant and the rpm reduced, but the noise increasing for the 50% case when the rpm was kept constant and the pitch changed. He demonstrates clearly that: ‘*...when the speed (under the constant rpm mode) is reduced the noise increases!*’

Anecdotal evidence suggests that CPP ships may generate more hydro-acoustic noise than FPP ones, however, there are many CPP warships. This shows that a well designed CPP can generate low noise, albeit that this is probably more relevant to the cavitation inception speed than to noise generated during cavitation at high speed operations. There is little data in the public domain about warship noise above CIS, however it is likely that they are still quieter than a noisy merchant ship at the same speed.

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[3] Hotel load is the load required to run the ancillary services.

Getting the correct control algorithm to give the right balance between varying pitch and varying rpm is considered vital for warship applications. (See, for example van Terwisga *et al* 2004.) It may be that this aspect could be improved for CPP merchant ships too, and it is recommended that this be investigated.

It should be noted that it is not feasible to retrofit a ship designed for a CPP with a FPP.

Propulsion system

Although most large conventional merchant ships are propelled by direct drive low speed diesel engines, there are some ships, notably cruise ships, that use diesel-electric or gas turbine-electric drive systems. These have the advantages of being able to change rpm on the propeller quickly, including reverse thrust, and of being able to use the same engines to develop power for auxiliaries and hotel loads as propulsion. Many such vessels use podded drives, where the electric motor is housed in an azimuthing pod, and the propeller is mounted in tractor configuration[4]. This also gives very good low speed control as the thrust can be vectored as required. Combined with bow thrusters this permits excellent low speed manoeuvring, often doing away with the need for tugs when berthing.

Podded propulsion also provides the benefits of being able to align the pods with the inflow, which is usually upwards at the stern of a vessel (and inwards for twin screws). Together with the tractor configuration this can result in much better flow into the propeller(s). Podded propulsion has been proposed for warships too as the better inflow will reduce the noise and vibration from the propeller (Ball, 2001).

Ships using diesel-electric configuration usually use medium speed, rather than low speed diesels. There is more freedom regarding where the engines are located, and combined with the ability to mount them on isolation systems means that the potential to reduce noise (both internal and external) is increased. This is another reason for using such systems on cruise ships.

Hence, diesel-electric ships have the potential to be far quieter than direct drive diesel ones. However, it is unlikely that such a configuration will be adopted by the majority of the large merchant ship fleet as it is generally more costly, and less efficient for most applications.

Number of propellers

Although by far the majority of merchant ships are propelled by a single propeller, there are a some, including cruise ships and ferries, that have twin screws. It is normal for twin screw vessels to have their propellers rotating in opposite directions. The propeller on the starboard side will rotate in the opposite direction to the one on the port side. The propellers can be turning with the propeller tips moving towards the vessel centreline at the top (inward turning propellers) or with the propeller tips moving away from the vessel centreline at the top (outward turning).

Usually the choice of either outward turning, or inward turning is dependent on efficiency at the design speed range, although sometimes the difference in low speed manoeuvring characteristics will have an influence on the choice.

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[4] Tractor configuration is where the propeller is ahead of the pod, and pulling, rather than pushing. This means that the presence of the pod has minimal influence on the wake into the propeller.

It is interesting to note that a recent investigation into the rotation direction on an existing twin screw vessel found that by changing the direction of rotation from outward to inward resulted in the broadband energy in the 5 to 100 Hz range being reduced by almost 90% (Kinns and Bloor, 2000). This is not to suggest that inward turning propellers will always give such an improvement over outward turning ones, simply to illustrate the difference obtainable from careful analysis.

2.8 Effect of speed

As noted above, most merchant ships will suffer from cavitation as they will be operating above the cavitation inception speed. If these ships were all to operate below this speed then the hydro-acoustic noise levels would be reduced considerably. However, as cavitation inception speed is likely to be around 10 knots, or lower, for many merchant ships, this is clearly impractical. Therefore, merchant ships will be exhibiting some level of cavitation, and so the effect of speed over the cavitating range only will be considered.

Although there is only very 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 noise. It is recommended that further full scale trials be conducted to investigate the effect of speed on hydro-acoustic noise across a range of vessel types.

Comprehensive experiments were conducted on a military coal carrier fitted with a fixed pitch propeller which showed that for speeds higher than the cavitation inception speed: '*the overall level (in dB) of the noise spectrum increases smoothly with speed according to 104 log (rpm), or about 31 dB per double speed*.' (Arveson and Vendittis, 2000). Earlier measurements made on small craft also showed a linear relationship between the noise level in dB and the log of the speed (McCauley *et al*, 1996). Note that over the speed range being considered the ship speed is roughly proportional to rpm.

More recent work has also shown that increasing speed results in increased hydro-acoustic noise (Wittekind, 2008).

This implies that, in the absence of other data, the relationship between speed and power can provide an indication of how noise output may be affected by changes that result in small increases in efficiency due to cavitation reduction. It is recommended that the relationship between power required for a given speed to the hydro-acoustic noise at that speed be investigated. This could be done in a cavitation tunnel where the delivered power to the propeller could be varied whilst the speed, and cavitation number based on speed, are fixed.

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 (Kipple and Kollars, 2004), this is not always the case. The reason is that when a ship is fitted with a controllable pitch propeller it reduces its speed not by reducing the shaft revolutions, but by reducing pitch. The problem with this, as explained above, is that the pitch will not be correct over the whole radius of the blade, resulting in inefficiency, and possibly excess cavitation.

As noted above, this can potentially be solved by modifying the combinator algorithm which governs the relationship between pitch and rpm for a given speed. This procedure is adopted by warships, and could potentially be implemented by merchant ships (van Terwisga *et al* 2004).

Thus, with a few possible exceptions, it is clear that reducing speed will reduce noise for the vast majority of large merchant ships.

PART II – Practical Technologies for Reducing Noise on Merchant Ships

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 cavitation inception speed. These specialised propellers typically cost about 15 – 20% more than conventional ones due to additional design effort, additional model testing, and better casting and machining.

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 discussed are those which claim to increase the efficiency, and thereby reduce the running costs.

3. Standard propeller technology

3.1 Existing propeller blades

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% - obviously depending on the damage (Townsin *et al*, 1985). Such damage should be repaired during routine dry dockings. In addition, a certain amount of polishing can also be conducted afloat between dockings, which will ensure the propeller remains as efficient as possible.

Further, such imperfections can have a significant effect on the local cavitation, and hence result in an increased level of hydro-acoustic noise. To date this has not been quantified. It is therefore recommended that controlled tests in cavitation tunnels on undamaged and damaged propellers be conducted to determine the effect that various levels of damage will have on the hydro-acoustic noise generated by the propeller.

Repairing propeller blades, whilst in dry dock, is not a particularly difficult task. Although the exact cost will depend on the size of the propeller, and the level of damage, this is likely to be in the order of US$20,000, or thereabouts. It is therefore recommended that this be considered for all vessels as part of their normal dry dock. It has also been suggested that an inspection be conducted every six months (Patience, 2000).

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% (Mutton *et al* 2006, 2005, Atlar *et al*, 2002). Such coatings can be effective for in excess of 36 months.

There have been some reports that these coatings can also reduce the noise. Recent measurements in a cavitation tunnel have been inconclusive (Mutton *et al*, 2006). Whilst there are noticeable noise reductions at some loading conditions for some frequencies this is not always the case. Also, it was noted that when cavitation was more severe (*ie* in ballast) the effect was less noticeable. Therefore, because it does not appear to reduce the noise in the more extreme cavitation situations, is it is not so likely that this will make a big difference to the noisiest of merchant ships. However, it is recommended that this be investigated further.

It should be noted that if the hydro-acoustic noise were to be continually monitored it *may* be possible to use this to determine how much deterioration is occurring on a propeller over a period of time. This could then possibly also be used to determine when it would be cost effective to clean and/or repair a propeller to improve its efficiency. This will not be easy to achieve, however it is recommended that it be considered further.

3.2 New 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 operated at a percentage of the maximum continuous rating (MCR), typically 80 – 90% MCR. 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.

In addition, most propellers are designed for full load condition, in calm seas, whereas many ships operate at lighter draughts in a seaway.

Finally, many owners are adopting ‘slow steaming’ philosophies, to reduce fuel consumption. This will also mean that the propeller has not been designed for the correct conditions.

Once a ship has been operating for a number of years, if careful records have been taken it will be possible to better understand the actual operating conditions for the propeller, and a redesign undertaken, if appropriate. It may then be possible to modify the existing propeller, or it may be desirable to manufacture a new one.

This may result in better efficiency, and improved cavitation characteristics. Clearly, the level of improvement will depend on how far the actual operating conditions are from those used for the original design.

Depending on the changes that are required, it may be possible to modify the existing propeller.

If it is not possible to make the changes with the existing propeller, then a new one could be manufactured. The cost of a new propeller will depend on the size of the vessel. Whilst it is difficult to get generic estimates, approximate cost for a conventional fixed pitch propeller are given in tables 3.1 and 3.2. These are certainly not claimed to be accurate figures, as the cost will depend on a wide range of design factors, shipping costs, costs of material, and finish required.

Table 3.1 Approximate propeller costs for tankers and bulk carriers

Deadweight (tonnes)	Approx cost (US$k)
30,000	300
70,000	400
110,000	650
200,000	1,300
300,000	1,600

Table 3.2 Approximate propeller costs for containerships

TEU[5]	Approx cost (US$k)
2,000	600
5,000	1,300
8,000	2,000
11,000	2,400

If fitted during a standard dry dock this could take as little as one day, whereas if the ship was to be docked especially for this purpose it would take about seven days (docking, fitting the new propeller, and undocking).

3.3 Dry docking costs

Dry docking costs are very difficult to estimate, as this will depend very much on the size of the vessel, the location, and exactly how long the operation will take.

As a guide, it is anticipated that if a ship needs to be docked to change a propeller then this will take about seven days. The cost for this is will vary between about US$60k and US$200k for a small 20,000 dwt ship to up to US$250k for a 200,000 dwt[6] vessel. Dry docking facilities prefer not to tie up their docks for a simply operation like changing a propeller, where they can’t make use of much of their labour and hence may well charge a premium.

Changing a propeller during a routine dry dock will cost substantially less than this, but the amount will depend on a number of factors, so it has not been possible to obtain an estimate.

It should be noted that it may be possible to change a propeller without docking the ship, at least for the smaller sized vessels, by trimming it by the bow. This could reduce the cost substantially if it is possible. Again, detailed costs are not available, however one estimate is that it would take about the same length of time, and cost about half the cost associated with docking the vessel.

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[5] Twenty foot equivalent units.

[6] Deadweight (tonnes).

4. Special merchant ship propellers

4.1. Introduction

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

Many surface warship and research vessel propellers are designed to avoid cavitation altogether below a given speed, known as the cavitation inception speed (CIS). This results in a propeller which is a few percent less efficient than a conventional merchant ship propeller, and hence is 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. Some of these are well summarised by Ligtelijn (2007).

There are also a number of propriety propeller design concepts that claim increased efficiency and a reduction in cavitation/vibration. The cost of these is likely to vary between being the same as a conventional propeller (see tables 3.1 & 3.2), to perhaps 10 – 20% higher.

It is important to recognise that the claims reported by the proponents of these concepts have not been independently verified for this project. Also, although claims of reducing cavitation are made, it is not clear exactly how much these will reduce the external hydro-acoustic noise generated that propagates into the water. Most of the emphasis of the concepts is to increase efficiency, and to reduce noise and vibration propagating into the ship.

However, as noted in Section 2.8 noise levels in dB appear to be roughly linearly proportional to the log of the speed. As power is roughly proportional to the cube of the speed, there is some tentative evidence to suggest that noise levels may be reduced by the cube root of power required for a given speed. It is recommended that this be investigated further.

It is also strongly recommended that dedicated acoustic trials be conducted to confirm the designers’ claims.

A selection of well known alternative propeller designs are discussed, however it is important to recognise that there are many others, and that different approaches may suit different vessels.

4.2. High skew propellers

One generally accepted way of reducing the vibration and fluctuating noise from a propeller is to increase its skew. A photograph of a highly skewed propeller is given in figure 4.1, courtesy of MAN Diesel A/S Denmark. This has the combined effect of causing the blade to pass through the varying wake field (particularly near the top of the cycle) in a more gradual manner, and in improving the cavitation pattern on the blades. Together with reduced tip loading, very highly skewed propellers can have a significant influence on reducing propeller induced vibration (Breslin and Anderson, 1994). Highly skewed propellers are commonly used in warships to reduce noise and vibration. Skewed propellers are also used in many high powered merchant ships where propeller induced vibration may pose a problem.

Whilst high skew can reduce blade rate excitation, it is noted that it may have a counterproductive effect on the formation of vortex types of cavitation, and hence too much skew may cause broadband excitation (Ligtelijn, 2007). It is recommended that the effect of skew on a propeller noise for a typical merchant ship under normal cavitating operations be investigated.

The cost for a typical skewed propeller will be similar to that of a conventional propeller, although the costs for a very highly skewed propeller may be 10 – 15% greater.

Figure 4.1 Highly skewed propeller
(Photography courtesy of MAN Diesel A/S Denmark)

4.3. Contracted and loaded tip propellers

The Contracted and Loaded Tip (CLT) propeller is offered by the Spanish designer, SISTEMAR. These propellers are designed with an end plate which reduces the tip vortices, thereby enabling the radial load distribution to be more heavily loaded at the tip than with conventional propellers. In turn, this means that the optimum propeller diameter is smaller, and there is the possibility of reducing cavitation. However, the propeller needs to be designed very carefully.

A photograph of a typical CLT propeller is given in figure 4.2.

Figure 4.2 Typical CLT propeller
(Courtesy of SISTEMAR)

Although there has been some academic work done on the optimisation of propellers with end plates (de Jong 1991) the information on the performance of CLT propellers is based on that provided by SISTEMAR (SISTEMAR, 2005).

SISTEMAR (2005) refers to comparative trials on two sister ships (164,000 dwt bulk carriers) where the ship fitted with the CLT propeller required 12% less power for the same speed.

This same article also refers to a retrofit of CLT propellers to a *Fortuny*, a twin screw fast ferry built in 2001 with a length between perpendiculars of 157m, and a displacement of 15,327 tonnes. This vessel had been suffering from vibration problems. After fitting the CLT propeller reductions in power required from 11% at 21 – 24½ knots to 30% at 15 knots, together with considerable reductions in the pressure spectrum from the propeller are claimed.

According to SISTEMAR the cost of a typical CLT propeller is likely to be about 20% more than a conventional propeller. The cost of eight blades for *Fortuny* was about US$325k (in 2005). Conventional blades for a similar sized ferry would probably cost about the same today.

4.4. Kappel propellers

Kappel Propellers are another approach to modification of the propeller tip to reduce tip vortices. In this case the tips are smoothly curved towards the suction side of the blades and increases in efficiency of approximately 4% are claimed (Anderson, *et al*, 2000). A photograph of a Kappel propeller is given in figure 4.3, courtesy of MAN Diesel A/S, Denmark.

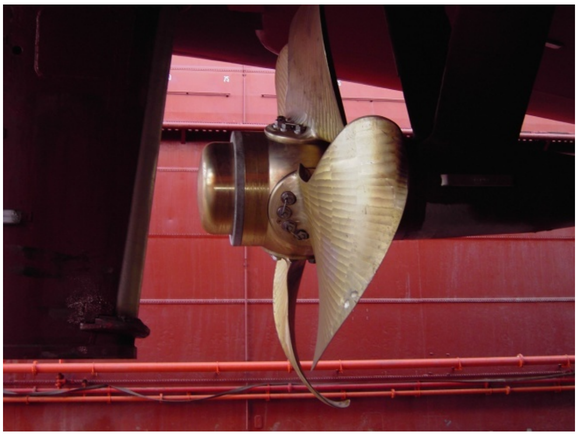

Figure 4.3 Kappel Propeller
(Courtesy of MAN Diesel A/S, Denmark)

Although it is reported by Andersen *et al* (2000) that a Kappel propeller can be used to reduce cavitation, and increase efficiency, recent correspondence with MAN Diesel A/S Denmark has suggested that this may not be the best approach to reducing hydro-acoustic noise. It is considered that this concept ought to be studied further.

4.5. New blade section propellers

The New Blade Section (NBS) propeller is referred to as a high efficient propeller which the designers claim can provide higher efficiency and superior cavitation performance when compared to a conventional propeller due to an improved blade cross section. It also has a smaller diameter, permitting a lower ballast draught to satisfy propeller tip immersion (Sasaki and Patience, 2005).

There is no reason why such a propeller would be more expensive initially than a conventional propeller, and it is claimed that as it produces less vibrations the overall capital cost of the propulsion system is less.

5. Propeller hub caps

5.1. Introduction

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 more steady 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.

A recent investigation has shown how 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 (Abdel-Maksoud *et al*, 2004).

It is not expected that the cost of a well designed hub cap would be much greater than one that has not been so well designed.

5.2. Propeller Boss Cap Fins

Propeller Boss Cap Fins (PBCF) are small fins attached to the propeller hub which are designed to reduce the magnitude of the hub vortices, thereby recovering the lost rotational energy, and reducing the cavitation. This concept has been developed by Mitsui OSK Lines Ltd. A photograph of a PBCF fitted to a propeller is given in figure 5.1.

Figure 5.1 Propeller Boss Cap Fins
(Courtesy of Mitsui O.S.K.Techno-Trade)

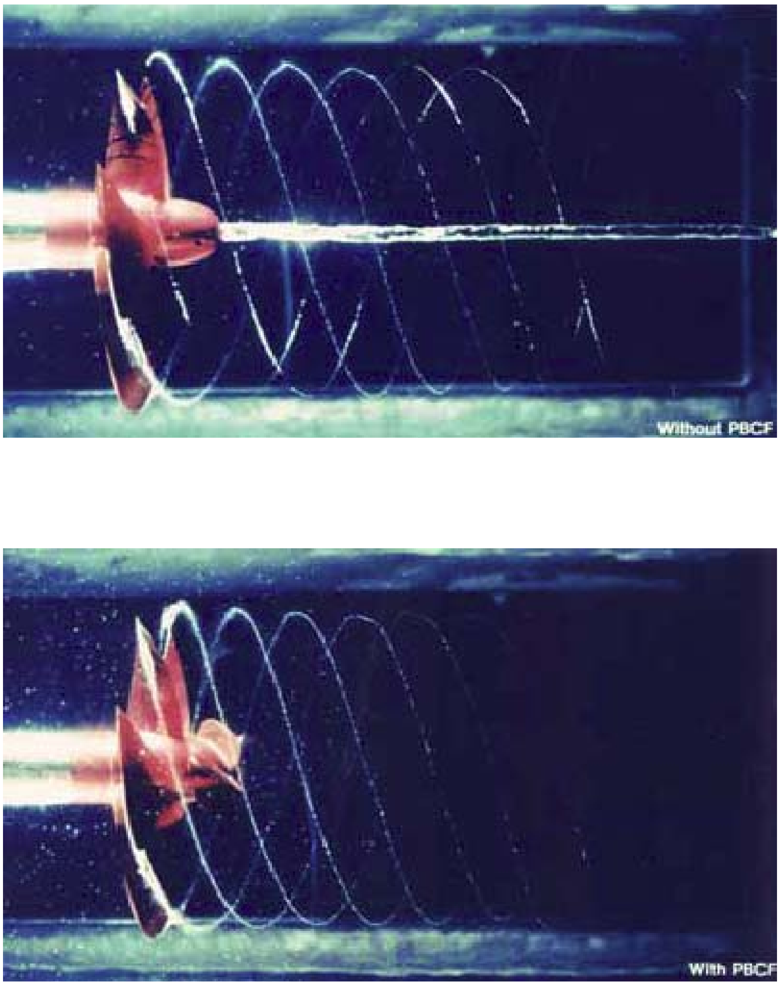

Figure 5.2 Effect of Propeller Boss Cap Fins on cavitation (Courtesy of Mitsui O.S.K.Techno-Trade)

There are a number of publications, largely by the proponents, discussing the benefits of the PBCF, however these are also well summarised by the International Towing Tank's specialist committee on unconventional propulsors (ITTC, 1999). Gains in efficiency of up to 7% have been reported, although gains of the order of 3-5% appear to be more common. An independent assessment has suggested gains of up to 3% (Mewis and Hollenbach, 2006).

Typical examples of costs for various ship types are given in table 5.1, taken from information provided by Mitsui OSK Techno-Trade Ltd. The fuel oil price used for this information was US$350/ton.

Table 5.1 PBCF costs (provided by Mitsui OSK Techno-Trade Ltd)

Ship type	Utilisation (%)	FOC[7] (t/d)	PBCF price (US$k)	Pay back period (months)
Containership	75	210	185	2.2
VLCC	85	100	165	3.6
Capesize Bulk Carrier	75	60	105	4.4
Handy Bulk Carrier	70	30	65	5.8
General Cargo ship	55	10	40	13.7

According to information provided by Mitsui OSK Techno-Trade Ltd experiments were conducted in a cavitation tunnel which showed that the PCBF caused a reduction in sound pressure level of 3 – 6 dB for frequencies exceeding 1,000 Hz. It is also claimed that the PBCF can be installed afloat in some cases, meaning that it is not necessary to dry dock the vessel. However, it would be reasonably simple to install this during a routine dry dock, and it is claimed that this could take less than five hours.

It is recommended that the claims made by Mitsui OSK Techno-Trade Ltd be verified. This could be done by testing in a cavitation tunnel capable of making appropriate noise measurements, and/or by full scale trials with sister ships where one is fitted with the PBCF and one is not.

5.3. Propeller Cap Turbine

An alternative approach to reducing the hub vortices is a Propeller Cap Turbine (PCT). This comprises a number of hydrofoil shaped blades integrally cast into the hub cap. As with the PBCF, energy from the rotating fluid coming from the propeller hub is recovered, resulting in energy savings. It is recommended that an independent study be conducted into the effect of PCT on hydro-acoustic noise.

The time to manufacture the PCT is about five months, and the weight of the unit is about 1 – 2% of the propeller weight. (www.shippropulsionsolutions.com).

A sketch of a PCT is given in figure 5.3, courtesy of Ship Propulsion Solutions, LLC.

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[7] Fuel Oil Consumption.

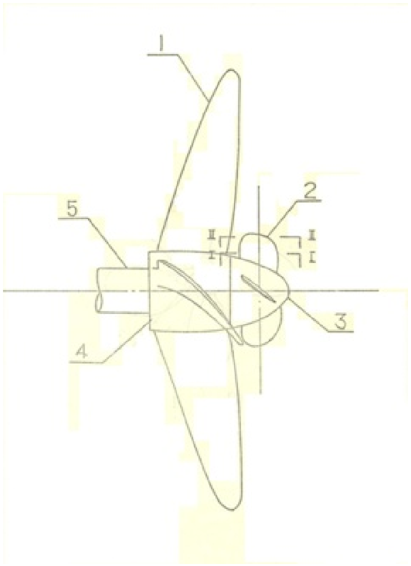

Figure 5.3 Sketch of Propeller Cap Turbine
(Courtesy of Ship Propulsion Solutions, LLC)

6. Wake inflow devices

6.1. Introduction

As noted above, the propeller operates in a non-uniform flow behind the ship. Although in general designers attempt to provide as good a flow to the propeller as possible, this is clearly limited by the desire to have as full a hull form as possible, to increase the carrying capacity of the vessel.

Improving the wake into the propeller will reduce cavitation, and probably also increase efficiency. This will depend on how bad the wake is in the first place – clearly if it is already very good then such flow modification devices will not improve the situation. However, if the wake is already good then the ship is not likely to be amongst the noisiest, and hence doesn't require to be addressed at this stage.

There are a number of devices that can be fitted to the hull of a ship to improve the flow into the propeller. These are discussed in various references including: ITTC (1999); Carlton (2007); Schneekluth (1987); and Breslin & Andersen (1994).

Johannsen reported on the benefits of vortex generators in reducing propeller induced hull pressure pulses by improving the wake flow into the propeller. He demonstrated greater than 50% reductions in all the first four harmonics, both at model scale and full scale (Johannsen, 2006). More recently, Carlton (2009) also gave a good example of how the flow around the afterbody of a container ship can be modified to resolve propeller cavitation induced vibrations using a system of vortex generators.

These devices can generally be retrofitted, either during a special docking, or during a routine docking, or can be included in the initial design.

It should be noted that the claims for improvements given below are taken from information supplied by the proponents, and that independent checks have not been conducted for this report. It is strongly recommended that dedicated acoustic trials be conducted to confirm the designers' claims.

A selection of well known alternative wake equalisation ducts are discussed, however it is important to recognise that there are many others, and that different approaches may suit different vessels.

6.2. Schneekluth duct

The Schneekluth duct is designed to improve the flow to the upper part of the propeller, and as such causes the formation of cavitation at the blade tips to be less pronounced, resulting in lower pressure pulse levels. (Kessler, undated). Although there is not actually data available, it is very likely that this will also reduce the cavitation noise generated by such vessels.

Fuel savings of up to 12% together with reductions in vibration of up to 50% are claimed (www.schneekluth.com). There are a number of examples where this has been successfully fitted to existing ships, although as noted above, the benefit is only going to be apparent if the wake is not very uniform in the first place.

According to the proponent, fitting the duct to a ship in dock takes only a few days, and can be done during a routine dry docking period. The total cost of the duct and associated spoilers for a 22 – 23 knot 2,500 TEU container ship is approximately US$120k, with the installation cost (during a scheduled dry dock) being about US$20k. According to information on the website an annual fuel saving of 1,200 tons of fuel is possible, giving a saving of about US$500k pa (assuming a fuel cost of US$410/ton). This results in a payback period of about four months.

It is claimed that there are more than 1,500 successful applications of this duct design, and that in many cases they have first been fitted to one ship of a class, and then fitted to the rest of the class (Kessler, undated).

Independent claims of improvements in propulsive efficiency of up to 4% have been made for this design (Mewis and Hollenbach, 2006).

Hence, such a technology is not only likely to be very beneficial in terms of reducing hydro-acoustic noise for the noisiest ships (*ie* those with very non-uniform wake fields) but can also be financially advantageous by increasing the efficiency of the propulsion system.

6.3. Mewis duct

The Mewis duct is designed by Becker Marine Systems. Again, the objective of this system is to improve the flow into the propeller.

This has apparently been used successfully for a VLCC (L = 318 m, B = 60 m, T = 20 m, speed = 16 knots, power = 22,000 kW) where a 5% fuel saving was achieved, resulting in an annual fuel saving of US$700k (Becker Marine Systems, Mewis Duct, undated brochure).

Again, this demonstrates the possibility of retrofitting a wake modification system to improve the wake, increase the propeller efficiency, and reduce cavitation/vibration.

6.4. *Simplified compensative nozzle*

The Simplified Compensative Nozzle (SCN) is another method of improving the flow into the propeller. The improved efficiency is achieved by re-shaping the nozzle to improve uniformity of wake flow into the propeller. This is accomplished by having a more vertical or cylindrical shape, rather than remaining circular. Also, it is claimed that the forming of the nozzle only requires rolling steel plates in a single direction, which reduces the cost of fabrication. (www.shippropulsionsolutions.com)

A photograph of a SCN is given in figure 6.1, courtesy of Ship Propulsion Solutions, LLC.

Figure 6.1 Simple Compensative Nozzle
(Courtesy of Ship Propulsion Solutions LLC)

6.5. *Grothues spoilers*

Grothues spoilers consist of a small series of curved fins attached to the hull just ahead of the propeller. They straighten the flow into the propeller, thereby improving the propeller efficiency. Claims of efficiency improvements of up to 6% for tankers and fully laden bulk carriers, and up to 9% for tankers and bulk carriers in ballast have been made (Schneekluth, 1987). More recently, independent claims of up to 3% have been reported (Mewis, and Hollenbach, 2006).

Although there is no information currently available on the reduction in cavitation, and hence noise, caused by these spoilers this is clearly possible, particularly for cases where the flow into the propeller is extremely non-uniform.

It should be noted, however, that if the wake is already good, then these spoilers will have minimal effect, and may even increase the drag on the ship.

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 (Molland and 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, as shown in figure 7.1, courtesy of Ship Propulsion Solutions, LLC. It is claimed that this can reduce the hydro-acoustic radiated noise levels in practice by 5 dB(A) (Ligtelijn, 2007). It is recommended that this be independently verified.

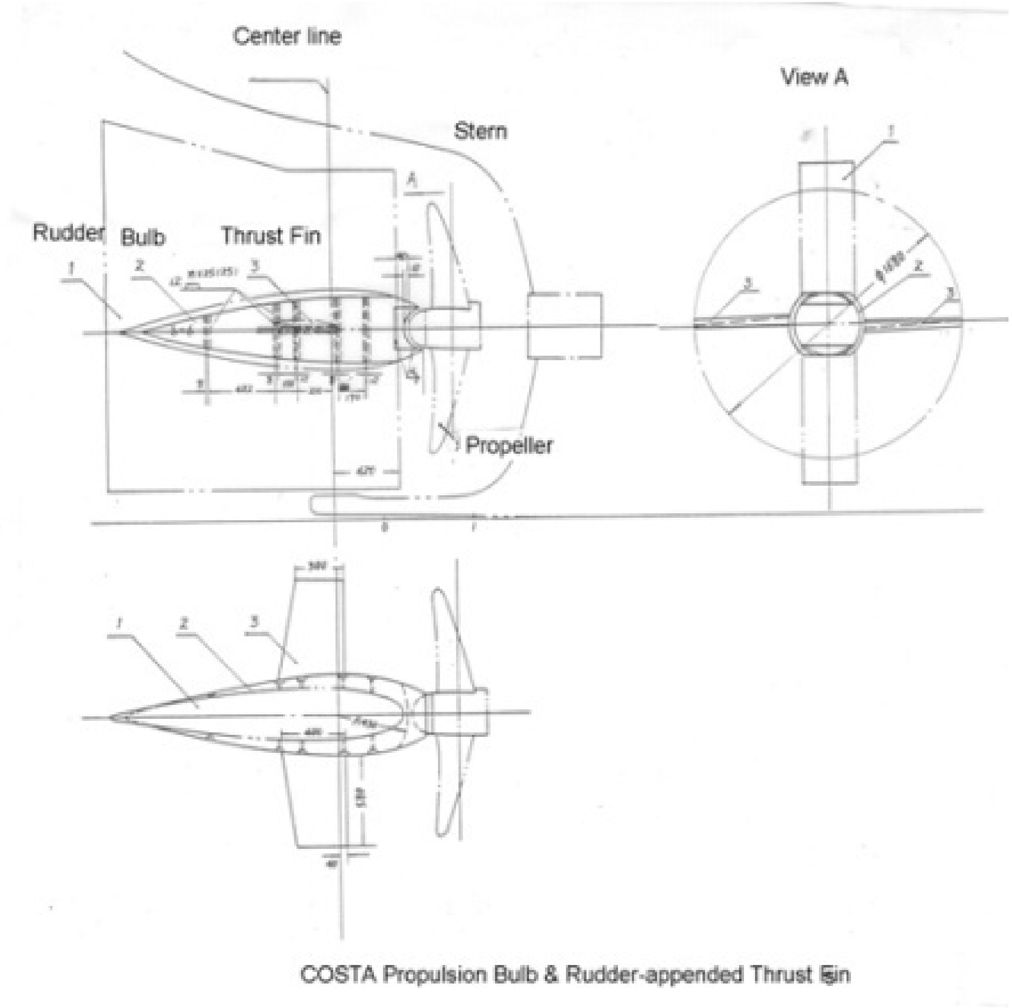

Figure 7.1 Costa Propulsive Bulb
(Courtesy of Ship Propulsive Systems, LLC)

8. Changes to the hull form

8.1. Introduction

The hull form will have a considerable influence not only on the power required to propel the vessel, but also on the hydro-acoustic noise propagating from its propeller. A well designed hull form will require less power for a given speed, which is likely to result in less noise being transmitted into the water.

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 noise being transmitted into the water.

Bearing in mind the importance of fuel efficiency it is very surprising that only about 5% of new build projects have the benefit of resistance and propulsion and propeller cavitation model testing during their design (Carlton, 2009).

It is well known that organisations specialising in hydrodynamic consultancies, such as the major hydrodynamics testing organisations, can often recommend substantial improvements to hull forms as a consequence of their extensive experience. Two good examples of such improvements by HSVA (formerly the Hamburg Model Test Basin) are given in Mewis, and Hollenbach, (2006). In one case (a Ro-Pax vessel) it was shown that lengthening the vessel by 3.5% reduced the power requirement by 15%, and in the other case (a product carrier) increasing the curvature of the turn of the bilge in the fore body resulted in a power saving of 8%.

Clearly, every effort should be taken with new builds to improve the hull form, where possible. Suitable tank testing and advice can be obtained from experienced hydrodynamics consulting organisations for in the region of US$100k – US$500k. Depending on their advice, a modified hull is likely to cost more than the initial design, but the trade off in performance may well pay for itself in a matter of a few years.

8.2 Asymmetrical afterbodies

One special technique for improving the flow into the propeller of a single screw merchant ship is to adopt an asymmetrical afterbody. The reason for this approach is that the flow around single screw ships is not symmetrical about the centreline, since the propeller is rotating 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 (Schneekluth, 1987, Breslin and Andersen, 1994).

9. Changes to operating procedure

As noted in Part I of this report, reducing speed will reduce the hydro-acoustic noise measured in dB generated by most merchant ships roughly proportionally to the log of the speed. Therefore, slow steaming could certainly be considered as a viable approach to reducing the total noise level, even although such slow steaming will require more ships to be operated to carry the same quantities of cargo.

In addition, slow steaming will reduce the propulsion power requirements. Roughly, the power required increases with the cube of the speed. However, as the time taken to cover a given distance will be linearly proportional to the speed, the saving in fuel for the propulsion for the voyage will be about proportional to the square of the speed. Against this, the voyage will take longer, requiring increased fuel for the hotel load, increased capital requirements, and increased crew costs to transport the same quantity of goods.

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

PART III – Practicalities and Likely Costs Involved with Measures to Reduce Cavitation Noise

10. Examples for different ship types

10.1. Introduction

In order to provide examples of the costs associated with the technologies described in Part II three examples are considered: a 20,000 dwt 1,500 TEU containership; a 250,000 dwt large tanker; and a 180 m long fast passenger ferry.

It is assumed that for each of these cases the ship is already operating, and that it has proven to be a particularly noisy vessel in its class.

It should be noted that it is not anticipated that any of these 'remedies' will have any influence on the general handling, or safety of the vessels concerned.

10.2. Containership

The example vessel is a 20,000 dwt containership, with a cruise speed of 19 knots. It is driven by a single fixed pitch propeller directly coupled to a slow speed diesel engine developing 15,000 bhp at 120 rpm. The daily fuel burn will be about 50 tonnes of Residual Fuel Oil.

In this example it is suggested that a comprehensive study into the wake and propulsive characteristics of the ship be undertaken. This will then result in a redesign of the propeller, and the fitting of vortex generators to the hull. In addition, a PBCF will be fitted.

Approximate costs for this are given in table 10.1. It should be noted that these are estimates only, and sufficient to give an order of magnitude cost only. The detailed costs will depend exactly on what is required, and on what sort of propeller is adopted, for example.

Table 10.1 Rough estimate of cost to retrofit 20,000 dwt containership

Item	**Approximate cost (US$k)**	
	Low estimate[1]	**Upper estimate[2]**
Detailed design studies, including CFD and model testing	100 – 200	100 – 200
Design and construction of new propeller	20 – 50	300 – 400
PBCF/PCT	100	100
Installation of propeller, vortex generators and PBCF/PCT	30 – 50	100 – 200
TOTAL	250 – 400	400 – 700

[1] assumes that the propeller only needs modifying, not replacing, and that all the work can be done in a scheduled dry dock period.

[2] assumes that a new specialist propeller is required (such as high skew, or CLT) and that this needs to be fitted at a dedicated dry dock period.

The increase in efficiency is likely to be about 5 – 10%, resulting in a daily saving of 2.5 – 5 tonnes. At a cost of US$650/tonne, this results in a daily saving of US$1,625 – US$3,250. Assuming that this ship is in transit for 320 days per year, this results in an annual saving of US$500k – US$1,000k.

10.3. Tanker

The example vessel is a 250,000 dwt tanker, with a cruise speed of 15 knots. It is driven by a single fixed pitch propeller directly coupled to a slow speed diesel engine developing 27,000 bhp at 60 rpm. The daily fuel burn will be about 100 tonnes of Residual Fuel Oil.

In this example it is suggested that a comprehensive study into the wake and propulsive characteristics of the ship be undertaken. This will then result in a redesign of the propeller, and the fitting of a wake equalising duct to the hull. In addition, a PBCF will be fitted.

Approximate costs for this are given in table 10.2. It should be noted that these are estimates only, and sufficient to give an order of magnitude cost only. The detailed costs will depend exactly on what is required, and on what sort of propeller is adopted, for example.

Table 10.2 Rough estimate of cost to retrofit 250,000 dwt large tanker

Item	**Approximate cost (US$k)**	
	Low estimate[1]	**Upper estimate**[2]
Detailed design studies, including CFD and model testing	100 – 200	100 – 200
Design and construction of new propeller	20 – 50	1,400 – 1,700
Design and construction of wake equalising duct	200 – 300	200 – 300
PBCF/PCT	200	200
Installation of propeller, wake equalising duct and PBCF/PCT	80 – 100	300 – 400
TOTAL	600 – 850	2,200 – 2,800

[1] assumes that the propeller only needs modifying, not replacing, and that all the work can be done in a scheduled dry dock period.

[2] assumes that a new specialist propeller is required (such as high skew, or CLT) and that this needs to be fitted at a dedicated dry dock period.

The increase in efficiency is likely to be about 5 – 10%, resulting in a daily saving of 5 – 10 tonnes. At a cost of US$650/tonne, this results in a daily saving of US$3,250 – US$6,500. Assuming that this ship is in transit for 320 days per year, this results in an annual saving of about US$1,000k – US$2,000k.

10.4. Fast passenger ferry

The example vessel is a 180 m twin screw passenger ferry, with a cruise speed of 24 knots. It is driven by four medium speed diesel engines delivering about 14,000 bhp each. These are coupled to two controllable pitch propellers through two twin input single output reduction gearboxes. Assuming that this is in transit for half its time, the daily fuel burn will be about 40 tonnes of Residual Fuel Oil.

In this example it is suggested that a comprehensive study into the wake and propulsive characteristics of the ship be undertaken. This will then result in a redesign of the propellers. Note that it may even be that a change in propeller rotation will be recommended (Kinns and Bloor, 2000), however this has not specifically been included in the cost estimates. In addition, a PBCF will be fitted.

Approximate costs for this are given in table 10.3. It should be noted that these are estimates only, and sufficient to give an order of magnitude cost only. The detailed costs will depend exactly on what is required, and on what sort of propellers are adopted, for example.

Table 10.3 Rough estimate of cost to retrofit 180 m passenger ferry

Item	**Approximate cost (US$k)**	
	Low estimate[1]	**Upper estimate[2]**
Detailed design studies, including CFD and model testing	100 – 200	100 – 200
Design and construction of new propellers	40 – 100	300 – 1,600[3]
PBCF/PCT	200	200
Installation of propeller blades, and PBCF/PCT	60 – 100	200 – 300
TOTAL	400 – 600	800 – 2,300

[1] assumes that the propellers only needs modifying, not replacing, and that all the work can be done in a scheduled dry dock period.

[2] assumes that new specialist propellers are required (such as high skew, or CLT) and that these need to be fitted at a dedicated dry dock period.

[3] the lower estimate is based on new propeller blades only, utilising the existing hub, whereas the upper estimate assumes that a completely new hub is required.

The increase in efficiency is likely to be about 5 – 10%, resulting in a daily saving of 2 – 4 tonnes. At a cost of US$650/tonne, this results in a daily saving of US$1,300 – US$2,600. Assuming that this ship is in transit for 300 days per year, this results in an annual saving of US$400k – US$800k.

PART IV – Concluding Comments and Recommendations for Future Research Needs

11. Discussion

Although there are only limited data on the propagated hydro-acoustic noise for merchant ships, it appears that there is a difference in noise levels between the noisiest ones and the quietest ones of the order of 20 – 40 dB (Carlton and Dabbs, 2009). This appears to imply that there is likely to be potential to reduce the noise generated by the noisiest ships.

It is almost certain that these noisiest ships suffer from greater levels of noise generated by cavitation than other merchant ships. Reducing the noise generated by cavitation is not a technology that is currently the main focus of the military as they concentrate on reducing the noise at speeds below cavitation inception speed, and on raising the cavitation inception speed as high as possible.

There is little known about what aspects of cavitation generate different levels of noise, above the general comments regarding the different forms of cavitation discussed in section 2.3. It is clear, however, that 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. Cavitation can, however, result in extreme vibration, and/or cavitation erosion which in some cases require remedial action. It is assumed that vessels with these problems are likely to represent the noisiest merchant ships, however at this stage there is no concrete evidence to confirm this. It is therefore recommended that this be investigated further.

Based on the assumption that ships with vibration problems are the most noisy, and that reducing these vibration problems will reduce the level of the noise propagating into the water, the available data suggests that there is the potential to reduce the noise of the noisiest merchant ships.

The two critical aspects influencing cavitation performance are the propeller design itself, and the wake into the propeller – which is dictated by the presence of the hull. Therefore, careful propeller design and careful hull design are essential prerequisites to improving the cavitation performance. Unfortunately, it appears that for many new builds there is not sufficient emphasis in the design effort put into such aspects, which it is assumed is the reason for many ships being noisier than others.

Based on this, it appears that it is quite possible that a considerable proportion of the noisiest merchant ships are likely to be operating at less than optimal efficiency. Many of the existing methods to increase efficiency for these vessels are also likely to reduce hydro-acoustic noise, and therefore the effect of these technologies on noise should be investigated further, as stated above.

It is important to note that the greatest improvements are likely to be achievable for ships operating at sub-optimal efficiency, however as noted above these are likely to be the noisiest ships.

12. Concluding comments

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).

Based on the current desk top study 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:

1. propeller design; and

2. 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. Depending on the changes required, the existing propeller could be modified, or a new one manufactured and fitted at the next scheduled dry dock.

In addition, there are a number of different propellers 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 (chapter 4). It is not known how these concepts will influence hydro-acoustic noise, however available data suggests that it is very likely that one or other of these concepts would also have this effect. Such a propeller could be fitted at the next scheduled dry dock.

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 (chapter 6). 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 – however it does seem very likely that they will do so.

The costs associated with retrofitting such technologies into an existing ship will depend exactly on what is required, and on whether it can be carried out during a scheduled dry docking, or if it will need a dedicated dry docking. For example, the costs associated with retrofitting a 20,000 dwt containership will be in the range of US$250k – US$700k, and those associated with retrofitting a 250,000 dwt tanker will be in the range of US$600k – US$2,800k. The increase in efficiency could result in an annual fuel saving of US$500k – US$1,000k for the containership, and US$1,000k – US$2,000k for the tanker.

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 in reduced hydro-acoustic noise.

13.Recommendations for future research needs

It is recommended that the following activities are required to better understand how to reduce the noise propagated into the water by conventional merchant ships:

1. Develop a standard method of conducting and analysing full scale noise measurements which should be adopted by those making measurements of the noise of conventional merchant ships. (Section 2.1).

2. Develop guidelines to help to identify the potentially noisiest large commercial ships. This will require making numerous full scale measurements on ships where the design features likely to influence noise are known, and relating these features to the measured noise. (Section 2.1).

3. Conduct a study into the relationship between the internal noise level on a ship (related to the propulsion system) and the level of noise propagated into the water. (Section 2.1).

4. Undertake an investigation into the effect of non-uniform wake on hydro-acoustic noise generated by a cavitating propeller. (Section 2.2).

5. Conduct more noise measurements in cavitation tunnels and full scale, and compare the results to determine the usefulness of conventional cavitation tunnels for noise measurements on merchant ships, and to determine the influence of scale effects. (Section 2.3).

6. Undertake an investigation into the effect of different types of cavitation on hydro-acoustic noise for a range of typical propellers for large merchant ships. (Section 2.3).

7. Undertake an investigation into the effect of ship loading condition, and proximity of the propeller to the free surface, on hydro-acoustic noise generated by the propeller, including the effect of the tip of the propeller breaking the water surface at the top of the cycle. (Section 2.6).

8. Undertake an investigation into the best way for combining pitch and rpm control on ships fitted with Controllable Pitch propellers to optimise the hydro-acoustic noise generated, and develop guidelines for this. (Section 2.7).

9. Conduct controlled full scale trials to investigate the effect of speed on hydro-acoustic noise for a wide range of different ships and ship types. (Section 2.8).

10. Undertake an investigation into the relationship between the delivered power required for a given speed to the hydro-acoustic noise at that speed. (Sections 2.8 and 4.1).

11. Conduct controlled tests in cavitation tunnels on undamaged and damaged propellers to determine the effect that various levels of damage will have on the hydro-acoustic noise generated by the propeller. (Section 3.1).

12. Undertake an investigation into the effect of propeller coatings on propeller generated hydro-acoustic noise under typical cavitating conditions for conventional merchant ships. (Section 3.1).

13. Investigate whether it is possible to use hydro-acoustic measurements to assess when the damage to a ship's propeller warrants repair. (Section 3.1).

14. Conduct independent dedicated acoustic trials to confirm the various claims of noise reduction made by the proponents of the different concepts identified in the report. This could involve testing on sister ships with and without the 'improvements', where possible. (Sections 4.1, 5.2, 5.3, 6.1, and 7).

15. Conduct an investigation into the effect of skew on a propeller noise for a typical merchant ship under normal cavitating operations. (Section 4.2).

16. Conduct an investigation to determine whether large merchant ships which have extreme vibration, and/or cavitation erosion which may require remedial action represent the noisiest merchant ships. (Section 11).

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