Appendix D: Reducing Underwater Sound to Protect Marine Life
Potential Treatments for Reducing Underwater Sound to Protect Marine Life.

By:
Sergiy Yatsenko; Mar. C/E
CSL Australia, Fleet Manager
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Low-frequency sound (LFS) emitted into the ocean by commercial vessels is an environmental perturbation that may have significant adverse effects on large whales, as they have evolved the ability to produce low-frequency sounds and highly adapted ears specialized for hearing underwater. Ambient noise is persistent background sound that is predominantly low-frequency (LF), and that has no single originating source or point. Today, ambient noise is dominated by aggregate ship traffic. Roughly 85% to 90% of the high levels of LFS radiated into the water by commercial vessels results from propeller cavitation, and is in roughly the same frequency range as calls produced by large whales.

Noise from distant shipping dominates frequencies from about 10-300 Hz worldwide, particularly in the 10-40 Hz frequency band. Fundamental frequency and harmonic components related to the propeller blade rate of commercial vessels dominate the infrasonic band (1-20 Hz).

Noise generated from ships is a function of ship size and speed. The larger, heavier, and faster a vessel, the louder the vessel. Large commercial vessels and supertankers (>135 m) today produce source levels about 160-190 dB re 1μPa·m, and future trends in cargo ship design emphasize increasing ship size and ship speed. Shipping traffic more than doubled LF ambient noise, increasing ambient noise levels by as much as 10-16 dB (10-40 times increase in sound pressure level), from that of a pre-propeller shipping ocean. The effects of such noise include no perceivable effects, masking important biological sounds, and inflicting irreparable damage to one or more animals.
Dolphins

Bottlenose dolphins produce whistle sounds within a frequency range of 0.8-2.4 kHz, and between 3.5-14.5 kHz at maximum energy. Source levels for bottlenose dolphins are in the range of 125-173 dB (re 1 μPa at 1 m). The finless porpoise is known to produce click sounds within a frequency range of 1.6-2.2 kHz and at 2 kHz at maximum energy (Ketten 1998a).

GENERAL SHIPPING

Surface shipping remains the most widespread source of low frequency (<1000 Hz) anthropogenic noise (e.g. Richardson et al. 1995, Simmonds & Hutchinson 1996, Popper et al. 1998). The US Navy (2001) has estimated that the +60,000 vessels of the world’s merchant fleet annually emit low frequency sound into the world’s oceans for the equivalent of 21.9 million days, on the basis that 80% of this fleet is at sea at any given time.

Ships generate substantial broadband noise from their propellers, motors, auxiliary machinery, gear boxes and shafts, plus their hull wake and turbulence. Diesel motors produce more noise than steam or gas turbines, but most long distance (low frequency) noise is generated by the ‘hissing’ cavitation of the spinning propeller. The characteristics of the principal sources of ship noise are as follows:

Propeller noise:

Originates from the propeller blade cavitation that forms gas-filled cavities whenever the pressure of the water accelerating over the face and any rough edges on each blade falls below critical values (propeller blades ‘suck’ ships forward by the very low pressures generated on their forward faces, and these rapid pressure falls cause the ‘boiling’ effect). Intense broadband sound is created when the bubbles subsequently collapse in either a turbulent stream or against the surface of the propeller. Cavitation noise is directly related to vessel speed (the faster the propeller rotates, the more cavitation plus the larger the wave wake, in which further air bubble generation and collapse occur).

For ships with constant pitch propellers, the intense ‘hissing’ noise begins above the cavitation inception speed (typically 7-14 knots for most merchant ships). For tugs, rig supply tenders and dynamically-positioned drilling ships equipped with variable pitch propellers, and/or thrusters, cavitation noise occurs at both low and high speeds, with cavitation-free speeds often restricted to the 7-10 knot range. Propeller blades also generate the distinct ‘blade-rate’ tones that are proportional to the rotation rate of the propeller, while ‘singing’ propellers are not uncommon but usually restricted to a narrow band of the vessel’s overall speed range.

Flow noise:

While most collapsing bubble noise is generated by propeller blade cavitation, other bubble noises emanate from obstructions on the hull and in the wave wake produced by the ship. Flow noise is sourced mainly from the external flow of water around the hull but also includes the noise of any fluids flowing through internal pipework that becomes transmitted through the hull. External flow noise includes vibrations and rattles in the hull plating and other external structures, plus the noise of the continuously breaking bow and stern waves and turbulence produced by protruding structures such as bilge keels, rudders and corrosion protection sacrificial anodes.
Machinery noise:

A range of mechanical vibrations that are generated by the main motors and auxiliary units and transmitted through the hull to the water, contributing to both broadband and narrowband noises. The noise spectrum radiated from merchant ships is typically 20-500 Hz with tonal peaks at approximately 50-60 Hz. Their low frequency noise components significantly contribute to the amount of low-frequency ambient noise, particularly in regions with heavy ship traffic. Thus ship noise needs to be treated in two categories; noise from nearby ships and that from distant traffic. Noise from nearby shipping is usually readily discernible as coming from individual vessels, with each ship producing a specific noise signature. The sound level and frequency characteristics (‘signature’) of discernible ships depend on their size, number of propellers, number and type of propeller blades, blade biofouling condition and machinery/transmission maintenance condition. In general, the larger the ship the louder the source level and the lower its tonals.

Table of different Source Underwater Noise Frequency and Level (re 1 μPa 1 m)

<table>
<thead>
<tr>
<th>Source</th>
<th>Peak frequency or band</th>
<th>Peak source level/s (re 1 μPa 1 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Icebreaking ship (full power in ice)</td>
<td>10-1000 Hz</td>
<td>193 dB</td>
</tr>
<tr>
<td>Large tankers and bulk carriers*</td>
<td>10-30 Hz</td>
<td>180-186 dB</td>
</tr>
<tr>
<td>Container ship**</td>
<td>7-33 Hz</td>
<td>181 dB</td>
</tr>
<tr>
<td>64 m Rig supply tender*</td>
<td>(broadband)</td>
<td>177 dB</td>
</tr>
<tr>
<td>Tug towing barge*</td>
<td>1000-5000 Hz</td>
<td>145-171 dB</td>
</tr>
<tr>
<td>20 m Fishing vessel*</td>
<td>(broadband)</td>
<td>168 dB</td>
</tr>
<tr>
<td>Trawler#</td>
<td>100 Hz</td>
<td>158 dB</td>
</tr>
<tr>
<td>25 m SWATH ferry with 2 x 950 hp inboard diesels**</td>
<td>315 Hz</td>
<td>166 dB</td>
</tr>
<tr>
<td>13 m catamaran with 2 x 200 hp inboard diesels*</td>
<td>315 / 1600 Hz</td>
<td>159 / 160 dB</td>
</tr>
<tr>
<td>Bertram cabin cruiser with 2 x 165 hp inboard diesels*</td>
<td>400 Hz</td>
<td>156 dB</td>
</tr>
<tr>
<td>8 m RHIB with 2 x 250 hp outboards*</td>
<td>315-5000 Hz</td>
<td>177-180 dB</td>
</tr>
<tr>
<td>Power boat with 2 x 80 hp outboards#</td>
<td>630 Hz</td>
<td>156-175 dB</td>
</tr>
<tr>
<td>4.5 m inflatable with 1 x 25 hp outboard*</td>
<td>2500-5000 Hz</td>
<td>157-159 dB</td>
</tr>
<tr>
<td>Zodiac inflatable with 1 x 25 hp outboard#</td>
<td>6300Hz</td>
<td>152 dB</td>
</tr>
<tr>
<td>Cutter-suction dredge (working)</td>
<td>100 Hz tonal</td>
<td>~180 dB</td>
</tr>
<tr>
<td>Clamshell dredge (working)</td>
<td>250 Hz pulses</td>
<td>150-162 dB</td>
</tr>
<tr>
<td>Pile driving operations</td>
<td>Low tonal pulses</td>
<td>170-180 dB</td>
</tr>
<tr>
<td>Seismic survey</td>
<td>0-1000 Hz</td>
<td>200-232 dB</td>
</tr>
<tr>
<td>Drilling</td>
<td>10-4000 Hz</td>
<td>154-170 dB</td>
</tr>
<tr>
<td>Supply vessel</td>
<td>1-500 Hz</td>
<td>182 dB</td>
</tr>
</tbody>
</table>

* recorded at 10-11 knots; ** recorded at ~15 knots; # unrecorded speed or speed range.
Data sourced from Richardson et al. 1995; Dames & Moore 1996; Au and Green 2000, McCauley et al. 2002; University of Rhode Island, undated; and DSTO data for the Port of Dampier.
PROPELLER TYPES TO REDUCE UNDERWATER NOISE.

Propeller Type:

**Water Jets or Pump Jet** (Pump sucks in H2O & squirts it out)
LFS Reduction: 15 dB
Rank: # 1
Approximate Cost: 6-10x that of standard prop if replacing ($600K - $1,000K)
- significantly reduces LFS
- speed not issue for LFS
- does as good on fuel as standard prop @ high speeds
- technology cost about same as new ship with propellers and shafting
- cost high if replacing previous propeller
- higher fuel cost for lower speed ships
- best option for new high speed ships
- worst option if replacing old ship technology

**Skewed** (skewed props reduce cavitation by raising speed of cavitation inception)
LFS Reduction: 10 dB
Rank: # 2
Approximate Cost: 2x to replace ($200K)
- good LFS reduction
- best replacement “fix”
- smooths cavitation & reduces frequency content
- no restriction on speed for LFS reduction or fuel cost
- fairly costly if used to replace previous propeller
- best option for replacement
- good LFS reduction for the cost
- next best option for new ships (second to water jets)

**Kort Nozzle** (duct fitted into a stator, prop fits into stator)

**Ducted Propellers**
A ducted propeller uses a duct around the perimeter of the propeller to modify the propulsion performance and noise characteristics of the propeller. The duct commonly employs an airfoil shape to either accelerate (Kort Nozzle) or decelerate (pump jet) the flow into the propeller.
This is done to enhance propulsion performance, cavitation performance, or both. A Kort Nozzle can increase propulsion efficiency by as much as 20% for heavily loaded propulsors by generating thrust over an airfoil duct shape. These configurations are commonly found on low speed vessels such as tug boats.
LFS Reduction: 5 dB
Rank: # 3
Approximate Cost: 3-5x to replace ($300K - $500K)
- good-fair LFS reduction
- useful on heavy tankers and bulk carriers
- cannot put on fast vessels
- not good LFS reduction for the cost
- not a good option
- does not work on high speed ships—cost high for LF reduction
Costs will naturally be higher compared to open propeller designs. However, overall efficiency may be increased depending on the specific design, thereby reducing fuel costs.

**Forward-Skew Blades in Duct**  
Unconventional, forward skew propellers have been implemented in ducted propeller designs and thrusters to significantly improve noise and thrust performance.  
The forward-skew blade design reduced underwater noise by 5-18 dB at the 1000 Hz third-octave band over much of the thruster’s operating range.  
After the new forward-skew blade was implemented the noise reportedly dropped by 20 dB at this frequency.

**CTP (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.  
According to SISTEMAR the cost of a typical CLT propeller is likely to be about 20% more than a conventional propeller.

**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%.  
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.

**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. Gains in efficiency of up to 7%.  
According to information provided by Mitsui OSK Techno-Trade Ltd experiments were conducted in a cavitation tunnel which showed that the PBCF caused a reduction in sound pressure level of 3 – 6dB for frequencies exceeding 1,000 Hz.

**Ring Propellers**  
This is a propeller that has a continuous ring attached to the blade tips (as opposed to using a duct). Because the tip clearance is effectively zero there is no loss of efficiency due to tip clearance effects. Open water efficiency is greater than for open propellers, although it is less than for ducted propellers. This approach removes the need to manufacture and install a separate duct and can have higher reliability. It is indicated that this design can have lower underwater noise,
although measured data was not identified.

**Voith Schneider Systems**

Voith Schneider systems operate in a very unique manner that is unlike almost any other propulsion system. The system is made up of several long blades that extend vertically downwards from the vessel, as seen in the image below. The operation of the system is described on the Voith Schneider website as follows:

... a rotor casing which ends flush with the ship's bottom is fitted with a number of axially parallel blades and rotates about a vertical axis. To generate thrust, each of the propeller blades performs an oscillating motion about its own axis. This is superimposed on the uniform rotary motion. Blade excursion determines the amount of thrust, while the phase angle of between 0° and 360° determines its direction. As a result, the same amount of thrust can be generated in any direction.

Voith Schneider systems can generate thrust in any direction, and have the ability to quickly change the direction of thrust. Such systems have been employed on many tug designs. These vessels can literally spin 360 degrees without any lateral motion. Voith Schneider systems are being used on European mine sweepers, and are therefore assumed to have some reduced noise levels relative to conventional systems. Additional details are not known.

- *Description of Estimated Costs*: Costs of installing Voith Schneider propulsion systems were not identified but are expected to be significantly higher than conventional systems due to increased complexity and uniqueness.

**Z-Drives**

Z-Drives and podded propulsion systems (also called ‘azipods’) use special gearing and machinery arrangements to locate the propeller further from the vessel / structure. This is done to achieve better inflow and outflow characteristics. These systems see less hull-wake deficit, reducing underwater noise. Furthermore, these systems can allow for steerable thrust, often covering a full 360 degree arc. Z-Drives also have the ability to be located in the middle or forward portions of the vessel.

Z-drives use a double-gear system to locate the propeller away from ship structures. In these systems, the prime mover is located on the vessel and is attached to the upper gear. The lower gear is located in the water and is then connected to the propeller. As a result of this arrangement, increased levels at gear mesh frequencies (100 – 5000 Hz range) may result, and can be significant if gear tolerance is poor.

**Podded Systems**

Podded systems have a submerged electric motor directly coupled to the propeller, without gearing. Podded propulsors are often operated with the propeller forward in a ‘puller’ configuration; this can provide a minimum of disturbed flow into the propeller. It is important to note that because the motor is in direct contact with the seawater this design **may not necessarily result in lower underwater noise at all frequencies.**

High noise levels at low frequencies (due to the motor) are evident in podded systems tested to date.
Azipod Propulsion System
An azipod system is similar to a Z-drive system in that the propeller is moved away from the ship, potentially providing lower radiated noise. However, the driving motor is located within the pod, removing the need for gears. Noise from the motor has proven to be significant in recent designs, but solutions are possible.

Beyond modification to the propellers themselves, other design choices can be made to locate the propeller in a position where there are better flow characteristics. This will help to reduce noise by delaying cavitation inception, but may yield a reduction in propulsive efficiency due to loss of the “wake fraction” factor. Such approaches include the use of drop-down thrusters, Z-drives, and podded propulsion systems. These approaches are best considered and implemented at the design stage.

The best option for noise reduction Propeller is AZIPOD System driven directly by Electric motor with no gear.
ENGINE AND GENERATOR UNITS

For the present, the only successful formula to meet the low noise requirement is based on diesel-electric propulsion. Figure below shows a layout of the section of a vessel where most of the main machinery is housed. The sources of power are the so-called ‘gensets’. These are units of combined diesel engine and alternator (AC).

Typically, there may be two, three, or even four such genset units, depending on the power needs of the vessel. This arrangement means that the gensets can be individually isolated from the hull to reduce the transmission of vibration and therefore minimise noise radiation into the water. A system of isolation is used where the diesel engine and generator are attached by isolators to an intermediate frame. The underside of the frame then has another set of isolators by which it is fixed to the seatings in the hull. Although this sounds like a simple process, much careful calculation and design is needed. As a rough guide the vibration levels at the feet of the engine need to be reduced by a hundred times or more at the seating in the hull. Both the diesel engines and the alternators must be selected for inherently low levels of vibration which requires high-quality well-designed and balanced machines to ensure that the vibration and noise level requirements are met.

PROPULSION MACHINERY NOISE

The power needed for the purposes of fisheries research vessels is likely to be from about 2 MW (2500 HP) to 6 MW (8000 HP) so large electric motors are required to drive the propeller. Vibration from a high quality electric motor largely reflects the nature of its power source so alternating current (AC) is not suitable and Direct Current (DC) becomes the obvious choice. We have already seen that the genset units contain alternators, so to drive the DC propulsion motor their output has to be converted to DC, using electronic systems that also allow precise control of vessel speed. Care has to be taken to avoid any residual of the frequencies from the drive control system (ripple) on the electrical supply to the motors because this would cause vibration. The large mechanical forces involved in propelling the vessels make it impractical to resiliently mount propulsion motors to isolate the inherently small vibration from the hull, instead, they are ‘hard-mounted’ in the vessel and directly coupled to the propeller shaft. Rotation of this shaft leads to the discrete ‘shaft rate’ frequency and its harmonics being generated and radiated into the sea.

For a shaft turning at 150 RPM the frequencies would be 2.5, 5, 7.5 Hz, etc.
Another noise reduction treatments, one of the most useful and cost effective for commercial vessels is selection of low noise / low vibration equipment. This approach has minimal impact on space and weight, and cost increases may be relatively small to moderate. Second to this, vibration isolation systems (resilient mounts) can be used to reduce structureborne noise from machinery, and will result in similar reductions in underwater noise (vibration isolation systems are very common on vessels of many types).

CONCLUSION

The overall design of power generation and propulsion systems can result in large reductions in underwater noise. Diesel electric systems have lower underwater noise levels than diesel-gear driven vessels. This arrangement readily allows the diesel generators to be resiliently mounted, thereby reducing underwater noise from vibrations. Electric motors have inherently lower noise and vibration levels than diesel engines, which would lead to reductions in underwater noise. If an electric motor required resilient mounting, this would be easier than for a propulsion diesel engine due to the reduced number of piping and other connections.

It is noted that diesel-electric propulsion systems can have greater overall efficiencies than geared propulsion diesel designs. This can be true in spite of the fact that a gearbox is more efficient than the conversion of power from mechanical to electrical and back to mechanical again. The reason for the overall increase in efficiency is that multiple small generators can be used; those generators that are needed can operate close to their optimal loading (i.e. near maximum) while others are secured. Therefore the overall diesel efficiency may be improved, resulting in a more efficient system at less than full load. Electric motors are lighter than diesel engines as well.

It is suggested that diesel-electric systems be considered when new vessels are designed in order to reduce underwater noise.

The total cost of machinery and propulsion treatments were discussed above estimate of $150K-$750K for a ‘first-order’ noise reduction depending of vessel type and size. This would include (roughly) resilient mounting treatment design and installation, airborne and secondary structureborne treatment design and installation, as well as analysis and installation of a modified propeller design. This cost is likely to be less than 1% of the total vessel cost. Actual costs and total noise reduction will naturally depend on the specific vessel.

Propulsion system have to be as 2-3 Diesel Generators producing power for 2x double/single Electric Motors drive by double gear 2xAziPod system propellers.

Diesel Generators are located within ER shell isolated at each side from the main hull.

Diesel Generators have to be mounted with dampers on to the intermediate base and that base via shock absorbers fitted to the ER bottom (floating base).

All Engine Room equipments such as pumps and auxiliary machinery to be resilient mount and low noise design.
REFERENCES

NOISE CONTROL ENGINEERING, Inc.
799 Middlesex Turnpike, Billerica, MA 01821, 978-670-5339, 978-667-7047 (fax)
nonoise@noise-control.com, http://www.noise-control.com
NCE Report 07-001 Treatments for Reducing Underwater Sounds

R.B. Mitson, Acoustec, Swiss Cottage, 5 Gunton Ave, Lowestoft, Suffolk NR32 5DA, UK
Tel: +44 1502 730 274., e-mail: acoustec@acoustec.co.uk
Theme Session: Use of Marine Research Vessels in ICES – Options for the Future
RESEARCH VESSEL STANDARDS: UNDERWATER RADIATED NOISE

Renilson Marine Consulting Pty Ltd
REDUCING UNDERWATER NOISE POLLUTION FROM LARGE COMMERCIAL VESSELS
March 2009, Commissioned by The International Fund for Animal Welfare

Review of Literature on Sound in the Ocean and Effects of Noise and Blast on Marine Fauna
Prepared for Western Australian Water Corporation,
URS Project No.: 42906896-1892 : R1340, 8 July 2008

Underwater Radiated Noise of Ocean-Going Merchant Ships
A Background Paper Produced by Participants of the International Workshop on Shipping Noise and
Marine Mammals
Held By Okeanos: Foundation for the Sea
Hamburg, Germany, 21st-24th April 2008

Causes and effects of underwater noise on fish abundance estimation
Ron B. Mitson a,* , Hans P. Knudsen b
a Acoustec, Lowestoft, UK
b Institute of Marine Research, Bergen, Norway
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