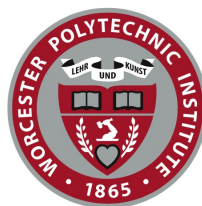




Catalog of Solutions to Reduce Marine Acoustic Pollution

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Supplemental Document

Accompanying

Methods to Minimize Commercial Vessel-Generated Marine Acoustic Pollution

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Advisors: Lorraine Higgins, Dominic Golding

Sponsor: United States Coast Guard

This document supplements the above named project and is submitted to the faculty of WPI in partial fulfillment of the requirements for the Degree of Bachelor of Science

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Contents

Analysis Table & Scale	1
Vessel Design	4
Combined Gas & Steam (COGAS)	6
Contracted & Loaded Tip Propeller (CLT)	8
Controllable Pitch Propeller (CPP)	10
Costa Propulsion Bulb	12
Diesel-Electric Propulsion	14
Highly Skewed Propeller	16
Hull Form Optimization	18
Kappel Propeller	20
Mewis Duct	22
New Blade Section Propellers	24
Number of Propeller Blades	26
Optimization of Engine Foundation	28
Podded Propulsion	30
Rudder Fins	32
Schneekluth Duct	34
Twisted Rudder	36
Waterjet Propulsion	38
Operational Practices	40
Hull Cleaning	42
Operational Speed Reduction	44
Propeller Cleaning	46
Additional Technologies	48
Acoustic Enclosures	50
Active Insulation	52
Air Bubble Curtain	54
Anti-Fouling Paints	56
Biomimetic Coatings	58
Elastic Mounting	60
Grothues Spoilers	62
Pre-Swirl Stators	64
Propeller Boss Cap Fins & Propeller Cap Turbines	66
Simplified Compensative Nozzle	68
Vortex Generator	70

Analysis Table & Scale

Evidence of Noise Reduction: Low/Medium/High

- Low:** Theoretical potential to reduce noise
- Medium:** At least 1 study with evidence of noise reduction
- High:** Measurable noise reduction

Market Availability: Yes/No

- Yes:** Currently available
- No:** Not commercially available, experimental

Cost: Report available data

Implementation: Retrofit/New Build

- EV:** Can be done on a retrofit
- NB:** Can be done on a newly built ship

Additional Maintenance: Low/Medium/High

- Low:** Little to no increase in maintenance
- Medium:** Risk of increase in maintenance
- High:** Definite increase in maintenance

Efficiency Impact: Positive/Neutral/Negative

- Positive:** At least 1 study with evidence of improved operational efficiency (fuel, power, hydrodynamic)
- Neutral:** Study shows no or insignificant impact on operational efficiency
- Negative:** At least 1 study with evidence of decreased operational efficiency

Method	Evidence of Nose Reduction	Availability	Cost	Implementation	Additional Maintenance	Efficiency Impact
Propellers						
Contracted & Loaded Tip Propeller	Low	Yes	20% higher than conventional propellers	EV/NB	Low	Positive
Controllable Pitch Propeller	High	Yes	EV Cost: \$224,441 - 336,662	EV/NB	Low	Positive
Highly Skewed Propeller	High	Yes	10-15% greater than conventional	EV/NB	Low	Negative
Kappel Propeller	Low	Yes	-	EV/NB	Low	Positive
Number of Propeller Blades	Medium	Yes	-	NB	Low	Negative
New Blade Section Propeller	Low	Yes	-	EV/NB	Low	Positive
Propeller Boss Cap Fins/ Propeller Cap Turbines	Medium	Yes	Estimated: \$55,000 - \$110,000	EV/NB	Low	Positive

Method	Evidence of Nose Reduction	Availability	Cost	Implementation	Additional Maintenance	Efficiency Impact
Hull						
Costa Bulb	High	Yes	-	EV/NB	Low	Positive
Grothues Spoilers	Low	Yes	-	NB	Low	Positive
Hull Form Optimization	Low	Yes	\$100,000 - 500,000	NB	Low	Positive
Mewis Duct	High	Yes	-	EV/NB	Medium	Positive
Pre-Swirl Stators	Low	Yes	-	NB	Low	Positive
Rudder Fins	Low	Yes	-	EV/NB	Low	Positive
Schneekluth Duct	High	Yes	~ \$140,000	EV/NB	Medium	Positive
Simplified Compensative Nozzle	High	Yes	-	EV/NB	Low	Positive
Twisted Rudder	Low	Yes	-	EV/NB	Low	Positive
Vortex Generator	Medium	Yes	-	EV/NB	Low	Negative
Alternate Propulsion						
Combined Gas & Steam (COGAS)	Low	Yes	Greater than Standard Diesel	NB	Low	Positive
Diesel-Electric	High	Yes	For Cruiser with power of 15 MW cost was 28% more to implement than conventional system	NB	Low	Positive
Podded Propulsion	Medium	Yes	-	NB	Medium	Positive
Waterjet Propulsion	Low	Yes	-	NB	Medium	Neutral

Method	Evidence of Noise Reduction	Availability	Cost	Implementation	Additional Maintenance	Efficiency Impact
Vibration Insulation						
Acoustic Enclosures	Low	Yes	-	EV/NB	Low	Neutral
Active Insulation	Low	Yes	Generally too high for commercial use	NB	Medium	Neutral
Air Bubble Curtain	Medium	Yes	-	NB	Medium	Neutral
Elastic Mountings	High	Yes	-	NB	High	Neutral
Optimization of Main Engine Foundation	Medium	Yes	-	NB	Low	Neutral
Hull Coating						
Anti-Fouling Paints	Medium	Yes	-	EV/NB	Low	Positive
Biomimetic Coating	Low	Unclear	-	EV/NB	Medium	Positive
Vessel Cleaning						
Hull Cleaning	Medium	Yes	Hull cleaning divers: \$1.5-2.5/m ² Hull cleaning robot: ~\$50,000	EV/NB	Low	Positive
Propeller Cleaning	Medium	Yes	~ \$3,000	EV/NB	Low	Positive
Vessel Speed						
Operational Speed Reduction	Medium	Yes	-	EV/NB	Low	Positive



Vessel Design

Contents:

Combined Gas & Steam (COGAS)
Contracted & Loaded Tip Propeller (CLT)
Controllable Pitch Propeller (CPP)
Costa Propulsion Bulb
Diesel-Electric Propulsion
Highly Skewed Propeller
Hull Form Optimization
Kappel Propeller
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New Blade Section Propellers
Number of Propeller Blades
Optimization of Engine Foundation
Podded Propulsion
Rudder Fins
Schneekluth Duct
Twisted Rudder
Waterjet Propulsion



Combined Gas & Steam (COGAS)

Overview:

Combined propulsion uses multiple small engines acting on the same propeller as opposed to a single larger one. One promising type already in use for land-based power generation is Combined Gas and Steam (COGAS), which uses a gas turbine paired with a steam turbine driven by the main engine's exhaust. Engines of this type can directly drive a propeller shaft, or be used to power an electric system (referred to as COGES). While these engines are more expensive than two-stroke diesels burning bunker fuel, they are also smaller, quieter, and more efficient.

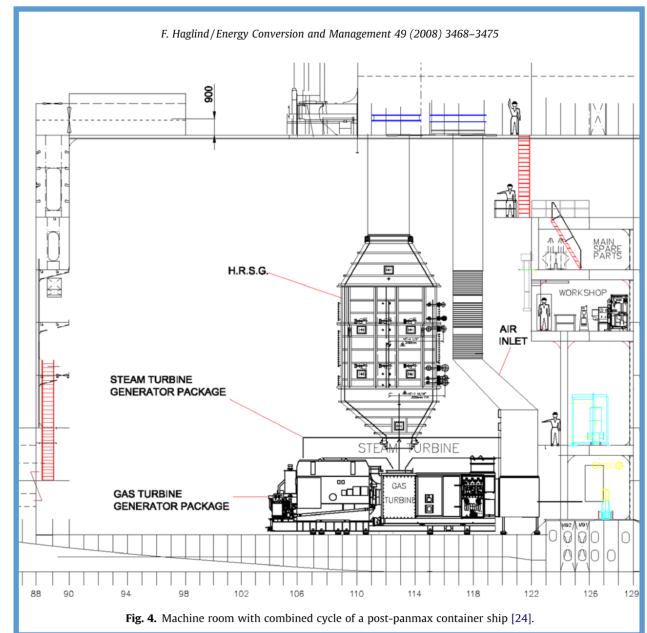


Fig. 4. Machine room with combined cycle of a post-panmax container ship [24].

Image from [1]

Cost

COGAS engines have greater first costs than marine diesel engines of equivalent power [1]. The natural gas they burn is also more expensive than bunker-grade fuel oil. However, they burn much cleaner, so future environmental regulations may make the question of fuel costs moot.

Noise Reduction

COGAS engines create less noise inside the ship than diesel engines of equivalent power [1]. How this translates to underwater noise has not been thoroughly studied.

Market Availability

COGAS engines have been in use for land-based power generation for some time. Several ships have also installed such engines [1].

Efficiency Impact

Marine COGAS engines have displayed efficiencies of up to 46.8% in regular use. In addition, their smaller size frees up space for additional cargo or passengers, increasing overall profitability [1].

Implementation

Best for new builds. Entirely replacing a ship's engine is a significant operation and may require replacing other parts (ex: propeller). Furthermore, taking advantage of the space freed up by the smaller engine may require alterations to the hull.

Additional Maintenance

Gas turbines use less lubricating oil than diesel engines and have fewer moving parts, lowering maintenance costs [1]. However, they are uncommon in the marine industry and may necessitate crew retraining.

References:

- [1] Haglind, F. (2008). A review on the use of gas and steam turbine combined cycles as prime movers for large ships. Part II: Previous work and implications. *Energy Conversion & Management*, 49 (3468-3475). DOI: 10.1016/j.enconman.2008.08.004



Contracted & Loaded Tip Propeller (CLT)

Overview:

Contracted and Loaded Tip (CLT) propellers have endplates on the pressure side of the blade tip to reduce the tip vortices. This distributes the radial load more heavily at the tip, allowing the optimal radius to be smaller, which has the potential to reduce cavitation [1]. CLT propellers can be retrofitted and applied to new builds [2]. Case studies have been done to compare the benefits of CLT propellers to conventional propellers. The case studied concluded that the CLT propeller was more satisfactory than the conventional propeller, reducing vibrations and improving overall ship efficiency [1].



Image from [3]

Cost

The exact of a CLT propeller is unavailable, but they are approximately 20% more costly than a conventional propeller [1][3]. Fuel savings can be expected due to the increase in fuel efficiency.

Noise Reduction

CLT propellers have potential to reduce noise. A reduction in vibrations have been noted, and a gain propulsive efficiency has been seen, which can theoretically cause a reduction in noise [1].

Market Availability

CLT propellers are commercially available. They have previously been implemented on tankers, bulk carriers, container vessels, roll-on/roll-off (RO-RO) ships, roll-on/roll-off passenger (RO-PAX) ships, car carriers, general cargo, passenger ships, and liquified natural gas (LNG) vessels [1].

Efficiency Impact

CLT propellers can achieve up to 8% higher propulsive efficiency than conventional propellers [1]. A case study tested a conventional propeller and a CLT propeller on two vessels. The vessel with the CLT propeller saw an 11% power reduction when travelling at 21-24 knots, and a 30% power reduction when travelling at 15 knots [3]. Also, at a low pitch, the CLT propeller cavitated less, and created lower pressure pulses on the hull [2].

Implementation

CLT propellers can be retrofitted and incorporated into new build designs. They can be installed on many commercial ships, including tankers, bulk carriers, container vessels, roll-on/roll-off (RO-RO) ships, roll-on/roll-off passenger (RO-PAX) ships, car carriers, general cargo, passenger ships, and liquified natural gas (LNG) vessels [1].

Additional Maintenance

There is no to little risk of additional maintenance for CLT propellers.

References:

- [1] AQUO Consortium. (2015). *D5.1: Comprehensive listing of possible improvement solutions and mitigation measures [PDF file]*. Retrieved from http://www.aquo.eu/downloads/AQUO_R5_9_List_Mitigation_Measures_rev1_0.pdf
- [2] AQUO Consortium. (2015). *D5.5: Impact of Solutions on Fuel Efficiency [PDF file]*. Retrieved from http://www.aquo.eu/downloads/AQUO_D5.5_Impact_Fuel_Efficiency_rev1.0.pdf
- [3] Renilson Marine Consulting Pty Ltd. (2009.). *Reducing Underwater Noise Pollution From Large Commercial Vessels [PDF]*. Retrieved from: <http://ifaw-pantheon.s3.amazonaws.com/sites/default/files/legacy/Reducing%20Underwater%20Noise%20Pollutions%20for%20Large%20Commercial%20Vessels.pdf>



Controllable Pitch Propeller (CPP)

Overview:

The controllable pitch propeller is a mechanically complex propeller that has the ability to control ship speed through a constant propeller rpm and varying blade pitch. Vessels using CPPs commonly reduce speed by varying the pitch, but this causes a non-uniform inflow of water to the propeller, increasing the effects of cavitation. To avoid this increase in cavitation, it has been shown that varying shaft speed rather than the pitch will lead to a reduction in propeller noise [1]. Some CPP's can reduce fuel consumption by varying the propeller rpm to operate at its optimal pitch [2]. CPP's have become an increasingly popular form of propulsion, because it's fine thrust control allows for easier maneuvering. This type of propeller is best applied to medium and high speed ships that operate on coastal or shorter routes [1], and has previously been applied to passenger and ferry ships, general cargo ships, and tug and trawling ships [3].

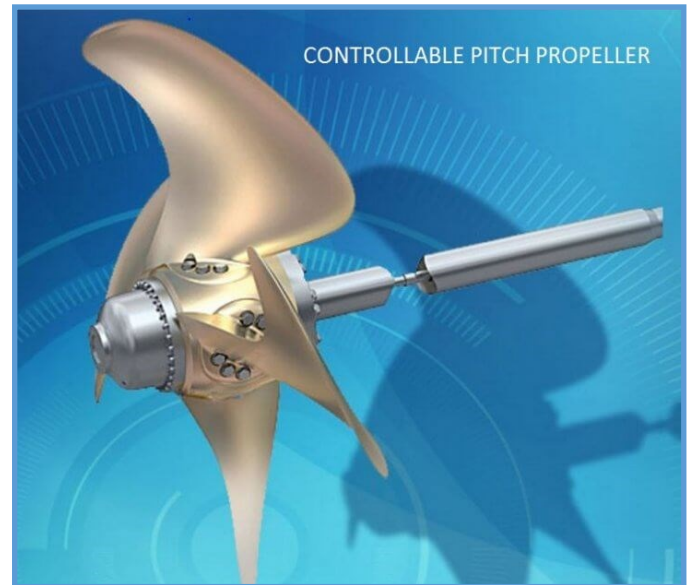


Image from [4]

Cost

The cost of both parts required for retrofitting, the governor and Variable Frequency Converter (VFC) drive system, is estimated at \$227,345-314,017 USD. Implementing a CPP on a new build will be less expensive than a retrofit. One study estimated that with the average cost of diesel is \$550 USD/ton, running at reduced speed could save approximately \$1000 USD/day [2].

Noise Reduction

Noise can be reduce up to 10-15 dB by a CPP if operated at optimal condition [2][4]. If operating at a reduced speed, an increased noise, cavitation, and fuel consumption may occur due to the non-optimal angle of the blade sections. A variable RPM engine is ideal with when using a CPP, because this allows the propeller to operate at optimal pitch, which reduces fuel consumption [2].

Market Availability

The CPP is favored over the fixed pitch propeller (FPP), making up 35% of the market as of 2007. CPPs has been implemented primarily on ferry and passenger, general cargo, and tug and trawling ships [3].

Efficiency Impact

Implementing a CPP and operating at 11 knots can save up to 20% fuel efficiency due to the decreased propeller power requirement. Travelling at slower speeds can increase this fuel savings. An additional 3-8% of fuel savings can be achieved through frictional losses, more efficient combustion, and power reduction [2].

Implementation

CPPs can be retrofitted, but with great difficulty. It must be noted that it is not feasible to retrofit a CPP to a ship with a FPP. To retrofit, the governor must be programmed to operate at variable RPM, and an VFC must be implemented to allow the grid voltage and frequency to remain constant when the engine speed is lowered [2]. CPPs can be incorporated into a new build design [4].

Additional Maintenance

Maintenance for the CPP can be expected to be lower than the conventional propeller. This will decrease the time for dry docking and maintenance costs, adding to the cost benefit of the CPP.

References:

- [1] AQUO Consortium. (2015). *D5.3: Assessment of the solutions to reduce underwater radiated noise [PDF file]*. Retrieved from http://www.aquo.eu/downloads/AQUO_D5.3_Assessment_URN_reduction_rev1.0.pdf
- [2] AQUO Consortium. (2015). *D5.5: Impact of Solutions on Fuel Efficiency [PDF file]*. Retrieved from http://www.aquo.eu/downloads/AQUO_D5.5_Impact_Fuel_Efficiency_rev1.0.pdf
- [3] Carlton, JS, 2007, *Marine Propellers & Propulsion*, Butterworth-Heinemann, (second edition) ISBN 978-07506-8150-6.
- [4] Renilson Marine Consulting Pty Ltd. (2009.). *Reducing Underwater Noise Pollution From Large Commercial Vessels [PDF]*. Retrieved from: <http://ifaw-pantheon.s3.amazonaws.com/sites/default/files/legacy/Reducing%20Underwater%20Noise%20Pollutions%20for%20Large%20Commercial%20Vessels.pdf>
- [5] Rolls-Royce (n.d.) *Controllable Pitch Propeller [JPEG]*. Retrieved from: <https://cultofsea.com/wp-content/uploads/2016/04/Controllable-Pitch-Propeller.jpg>



Costa Propulsion Bulb

Overview:

The Costa Propulsion Bulb is a proven approach to reduce propeller cavitation. It hydrodynamically integrates the propeller and the rudder by installing a bulb to the rudder in line with the shaft of the propeller [2]. As the sea water is pressed backwards due to vortexing from the propeller, the water will flow around the bulb and fundamentally increase the efficiency of the propeller [3]. However, as the bulb protrudes laterally, it is in the immediate danger zone, and has the potential to be damaged in the event of an impact or strong change in pressure before the rudder blade itself would be threatened [1].

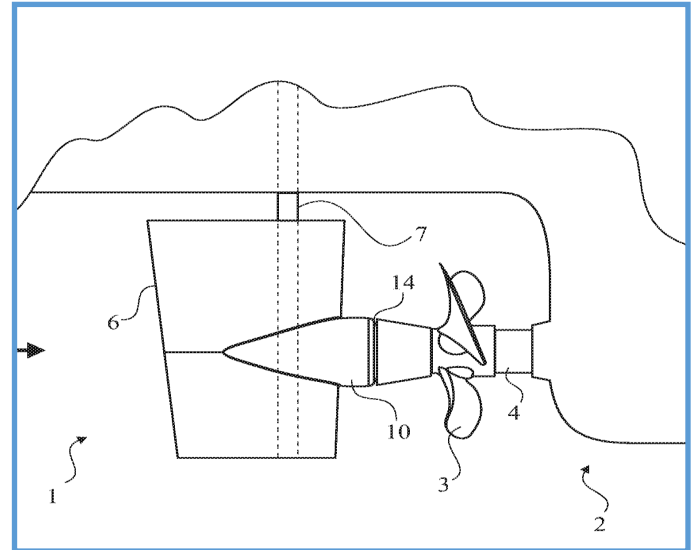


Image from [3]

Cost

No cost estimates are available, however the Costa bulb has a potential to become damaged, which will require extra repairs

Noise Reduction

By hydrodynamically integrating the propeller and the rudder with such a propulsion bulb, it is possible to significantly reduce propeller hub cavitation [2].

Market Availability

The Costa bulb and other energy saving devices that improve propeller efficiency have been available since the mid 1980's [4].

Efficiency Impact

The favorable flow that is produced by the Costa Bulb increases efficiency. It is recommended that the Costa bulb is used in combination with another noise dampening device to achieve increased fuel and propeller efficiency.

Implementation

This device can be implemented on both existing vessels and new builds, however it cannot be applied to vessels with turnable propeller units such as Z-Drives.

Additional Maintenance

Little to no additional maintenance is expected, however the potential to be damaged poses the risk of extra servicing.

References:

- [1] Kluge, M., & Lehmann, D. (2008). *U.S. Patent No. US20080110386A1*. Washington, DC: U.S. Patent and Trademark Office. Retrieved from: <https://patents.google.com/patent/US20080110386A1/en>
- [2] Leaper, R., Renilson, M., & Ryan, C. (2014). REDUCING UNDERWATER NOISE FROM LARGE COMMERCIAL SHIPS: CURRENT STATUS AND FUTURE DIRECTIONS. *The Journal of Ocean Technology, Vol. 9(No. 1)*. Retrieved from: https://www.researchgate.net/publication/261002250_Reducing_underwater_noise_from_large_commercial_ships_Current_status_and_future_directions
- [3] Pettersson, G., & Nerland, K. K. (2006). *U.S. Patent No. US7661379B2*. Washington, DC: U.S. Patent and Trademark Office. Retrieved from: <https://patents.google.com/patent/US7661379B2/en>
- [4] Shin, Hyun-Joon (2014). Numerical and experimental investigation of conventional and un-conventional preswirl duct for VLCC *International Journal of Naval Architecture and Ocean Engineering*, ISSN: 2092-6782, Vol: 5, Issue: 3, Page: 414-430. Retrieved from: <https://www.sciencedirect.com/science/article/pii/S2092678216303259?via%3Dihub>



Diesel-Electric Propulsion

Overview:

Diesel-Electric propulsion is a hybrid form of propulsion used commonly on cruise liners and research vessels. It utilizes diesel engines to power electric generators which are connected to electric motors that drive the shaft and propeller. Diesel-electric propulsion is significantly quieter than the two-stroke diesel engine, and has the added advantage of being able to be elastically mounted further reducing the vibrations. It is also a fuel efficient option for vessels that tend to vary their operating speed and power distribution. For most commercial vessels, diesel-electric propulsion will not be feasible because of a high initial investment cost and decreased fuel efficiency.

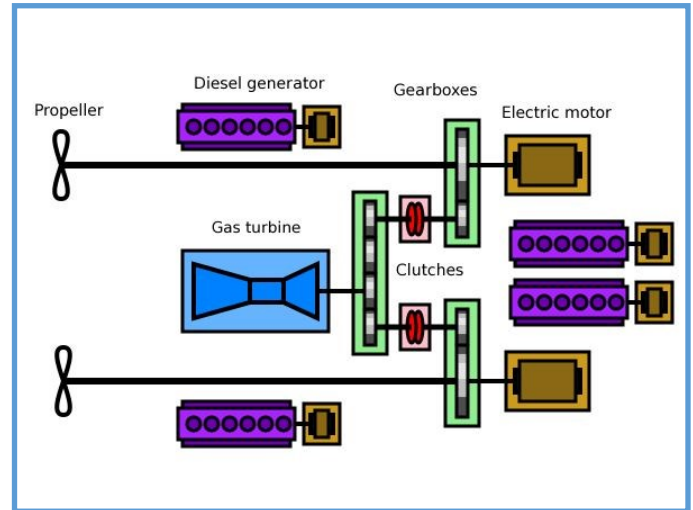


Image from [3]

Cost

Based on a 40,000 GRT cruise liner requiring 15MW of power the diesel-electric propulsion was 28% more expensive than the conventional mechanical powertrain [1]. ROI is unlikely to be seen by vessels operating at constant speeds.

Noise Reduction

A 10-20 dB reduction of machinery noise can be expected while using a diesel-electric system [1]. This benefits ships operating at low speeds where machinery noise dominates the total radiated noise.

Market Availability

The use of diesel-electric propulsion has seen exponential growth since 1995, where 269 units were in operation to 2013 where 1750 units were in service [2]. Continual improvements to electrical components are helping drive increased production.

Efficiency Impact

It is estimated that a cargo ship will consume approximately 7.5% more fuel using diesel-electric propulsion when compared to the standard mechanical diesel engine [1].

Implementation

Diesel-electric powertrains should only be considered for new builds. The electrical components offer flexibility for engines to be moved in different locations offering a wider design space.

Additional Maintenance

These systems are more reliable and require less maintenance than conventional mechanical propulsion. They also offer more system redundancies that improve reliability and improve safety [1].

References:

- [1] AQUO Consortium. (2015). *D5.5: Impact of Solutions on Fuel Efficiency [PDF file]*. Retrieved from http://www.aquo.eu/downloads/AQUO_D5.5_Impact_Fuel_Efficiency_rev1.0.pdf
- [2] Pestana, H. (2014). *Future trends of electrical propulsion and implications to ship design [PDF file]*. Retrieved from <https://pdfs.semanticscholar.org/43f4/3743d9474c03e1f80739970f9fe28f81aa66.pdf>
- [3] Ricky. (n.d). *Layout Out of Diesel Electric Propulsion in Ships [JPEG]*. Retrieved from <https://www.brighthubengineering.com/marine-engines-machinery/86300-diesel-electric-marine-propulsion/>



Highly Skewed Propeller

Overview:

The highly skewed propeller reduces noise and vibrations through its increased skew which allows the blade to gradually cut through the varying wake field, decreasing the cavitation generated. Reduced loading on a HSP tip can further decrease vibrations and noise from the propeller. HSP's are commonly used on warships and high powered merchant ships, where noise and vibrations can cause problems [5].



Image from [5]

Cost

HSPs are similar to the cost of a conventional propeller, although very highly skewed propellers can cost 10-15% more than conventional propellers [4]. There is no noticeable increase in fuel cost with a highly skewed propeller. If the propeller is damaged, the repairs can be more costly than repairing a conventional propeller

Noise Reduction

The HSP can achieve up to 10 dB of noise reduction and possible even higher when operating at a low frequency [1]. HSPs can increase the propeller's cavitation inception speed up to 2 knots [2]. When paired with an unloaded tip, HSPs can reduce propeller vibration and cavitation [5].

Market Availability

HSPs are commercially available, and are owned by MAN/Diesel (ECHO, 2017). These propellers are commonly implemented on warships and high powered merchant ships where noise can pose a problem [5].

Efficiency Impact

As of 1976, there was a small reduction in speed of up to 0.1 knots seen with HSPs. There was also a 5% decrease in propeller efficiency, causing an increase in fuel consumption [6]. Efficiency may have improved over the years, but information not is readily available.

Implementation

HSPs can be retrofitted and incorporated into new build designs. They have been used on warships and highly powered merchant ships, but implementation on merchant ships requires further investigation [6].

Additional Maintenance

There is no to little risk of additional maintenance required for HSPs. They are no more susceptible to damage than conventional propellers, and their blade erosion is equal to that of a conventional propeller [3].

References:

- [1] AQUO Consortium. (2015). *D5.1: Comprehensive listing of possible improvement solutions and mitigation measures [PDF file]*. Retrieved from http://www.aquo.eu/downloads/AQUO_R5_9_List_Mitigation_Measures_rev1_0.pdf
- [2] Boswell, R. J., & Cox, G. G. (1974, February). AD-777 038 Design and Evaluation of a Highly Skewed Propeller For a Cargo Ship. Retrieved from <http://www.dtic.mil/dtic/tr/fulltext/u2/777038.pdf>
- [3] Hammer, N. O., & McGinn, R. F. (1978). Highly Skewed Propellers—Full Scale Vibration Test Results ... Retrieved from <http://shipstructure.org/pdf/78symp18.pdf>
- [4] Hemmera Envirochem Inc. (2016). Vessel Quieting Design, Technology, and Maintenance Options for Potential Inclusion in EcoAction Program Enhancing Cetacean Habitat and Observation Program [PDF file]. Retrieved from <https://www.portvancouver.com/wp-content/uploads/2017/01/Vessel-Quieting.pdf>
- [5] Renilson Marine Consulting Pty Ltd. (2009.). *Reducing Underwater Noise Pollution From Large Commercial Vessels [PDF]*. Retrieved from: <http://ifaw-pantheon.s3.amazonaws.com/sites/default/files/legacy/Reducing%20Underwater%20Noise%20Pollutions%20for%20Large%20Commercial%20Vessels.pdf>
- [6] Valentine, D. T., & Chase, A. (1976, September). Highly Skewed Propeller Design for a Navy Auxiliary Oiler (AO 177). Retrieved from <http://www.dtic.mil/dtic/tr/fulltext/u2/a041189.pdf>



Hull Form Optimization

Overview:

Hull form optimization is a strategy that can be used to help improve the flow of water into the propeller. The hull form dictates how uniformly the water flows into the propeller, and, if optimized can greatly improve efficiency and potentially reduce underwater noise. There are no studies that have tied hull optimization to reducing noise, but it is well known that propeller cavitation is directly related to the inflow of water to the propeller. Investing in early model testing to design a well optimized hull could be a way for new vessels to both reduce their total noise output and improve their operational efficiency.

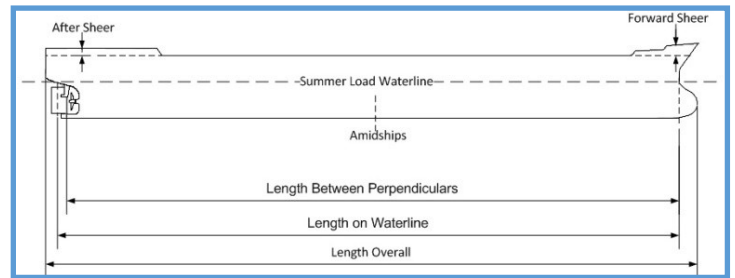


Image from [2]

Cost

Cost will vary depending on the application of the ship. It costs approximately \$100K - 500K to have a consulting agency do optimization testing, and the optimized hull specs will likely be more than standard design for that particular ship [3].

Noise Reduction

There is no evidence that optimizing hull dimensions reduces underwater noise. Cavitation performance of a propeller is tied into the inflow of water which is influenced by the hull form, so in theory optimizing the hull for improved flow will also reduce noise [3].

Market Availability

The ability to optimize the hull through computational model testing is available but not widely used. In 2009, only 5% of new builds utilized computational model testing to optimize hull form [1].

Efficiency Impact

Optimizing the hull can improve power efficiency. A Ro-Pax Vessel that was lengthened by 3.5% had its power requirement reduced by 15% [3]. Increasing the curvature of the bilge in the fore body for a Product Carrier saw powering savings of 8% [3].

Implementation

Optimizing the hull can only be applied to new builds. Model testing should be done early in the design phase to minimize costs, maximize efficiency gains, and achieve maximum underwater noise reduction.

Additional Maintenance

There is little to no risk of additional maintenance for an optimized hull.

References:

- [1] Carlton, JS, 2009, Ship hydrodynamic propulsion: some contemporary issues of propulsive efficiency, cavitation and erosion, Lloyd's Register Technology Day Proceedings, February 2009.
- [2] Kairis, S. (2012). Ship's Principal Dimensions [JPEG]. Retrieved from <https://officerofthewatch.com/2012/02/09/ships-geometry-and-hull-definition/>
- [3] Renilson Marine Consulting Pty Ltd. (2009.). *Reducing Underwater Noise Pollution From Large Commercial Vessels [PDF]*. Retrieved from: <http://ifaw-pantheon.s3.amazonaws.com/sites/default/files/legacy/Reducing%20Underwater%20Noise%20Pollutions%20for%20Large%20Commercial%20Vessels.pdf>



Kappel Propeller

Overview:

The Kappel propeller has an unconventional design, where the blade tip is curved towards the suction side, and the tip is loaded [1][5]. They have a low to moderate skew [5]. An increase in efficiency can be seen, but the level of noise reduction is in question. There are conflicting studies that report the Kappel propeller reduces cavitation and noise, while others state that there is an increase in cavitation and pressure pulses, and therefore more noise is created [1]. Kappel propellers can be retrofitted or incorporated into new build designs [1][5].



Image from [1]

Cost

Data on the specific cost of a Kappel propeller is unavailable. Savings can be expected due to the increase in fuel and hydrodynamic efficiency.

Noise Reduction

Whether Kappel propellers reduce noise or not is unclear. Mohammed et al. [2] suggested that Kappel propellers reduce cavitation and cavitation noise, while MAN Diesel A/S Denmark reported that this method may not be the best option to reduce noise [4]. Further investigation regarding noise reduction is needed.

Market Availability

Kappel propellers are commercially available. They are owned by MAN Diesel [3].

Efficiency Impact

A 4% increase in efficiency has been seen with Kappel propellers [2][4]. Fuel savings, reduced emissions, inhibition of the tip vortex, and greater thrust have also been reported. 3% less power is required when running at design speed [5].

Implementation

Kappel propellers can be retrofitted and incorporated into new build designs [1][5]. An increase in efficiency is greater for slower ships with a high block coefficient, such as tankers and bulk carriers [5].

Additional Maintenance

There is a no to little risk of additional maintenance required for Kappel propellers.

References:

- [1] AQUO Consortium. (2015). *D5.1: Comprehensive listing of possible improvement solutions and mitigation measures [PDF file]*. Retrieved from http://www.aquo.eu/downloads/AQUO_R5_9_List_Mitigation_Measures_rev1_0.pdf
- [2] Chekab, M. A. (2013). Investigation of Different Methods of Noise Reduction for Submerged Marine Propellers and Their Classification. *American Journal of Mechanical Engineering, Vol. 1 (No. 2)*. Retrieved from: https://www.researchgate.net/publication/275515444_Investigation_of_Different_Methods_of_Noise_Reduction_for_Submerged_Marine_Propellers_and_Their_Classification
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- [4] Renilson Marine Consulting Pty Ltd. (2009.). *Reducing Underwater Noise Pollution From Large Commercial Vessels [PDF]*. Retrieved from: <http://ifaw-pantheon.s3.amazonaws.com/sites/default/files/legacy/Reducing%20Underwater%20Noise%20Pollutions%20for%20Large%20Commercial%20Vessels.pdf>
- [5] Unconventional Tip Shape Propellers - SINM. (2014, September 9). Retrieved from <http://www.sinm.it/sites/default/files/Report350-14.pdf>



Mewis Duct

Overview:

The Mewis Duct improves both the ship's wake and rotational inefficiencies in the slipstream by the propeller fins. The only limitation to its increase in effectiveness is the requirement for the duct to have a smaller diameter than the propeller itself. It refines many components of propeller flow, first equalizing and stabilizing propeller inflow and maximizing the thrust output. Next, the duct integrates a pre-swirl fin system acting as a type of endplate to the fins. As the hub to propeller diameter ratio increases, the effect of reducing inefficient vortices also increases, which improves cavitation behavior. Vibrations are significantly lower according to crew feedback from retrofitted ships [2].



Image from [4]

Cost

No cost estimates are available.

Noise Reduction

Crew members of retrofitted ships gave positive feedback, reporting significantly lower vibrations. Cavitation is positively affected and the duct reduces vibration by reducing pressure pulses by 80%, among decreasing noise up to 8% [2].

Market Availability

Between 2008 and 2013, the Mewis Duct was very successful and over four hundred were delivered [1].

Efficiency Impact

Power saving can be seen between 4% and 8%, and average savings of 6.3% [1] [3].

Implementation

Tests and optimizations are recommended to develop the pitch settings of the fins. The Mewis Duct is preferred for ships whose speed tends to be less than 20 knots, i.e small container vessels and most tankers and bulk carriers [2].

Additional Maintenance

The Mewis Duct brings a potential risk of increasing maintenance. The duct has sharp corners that can be difficult to clean.

References:

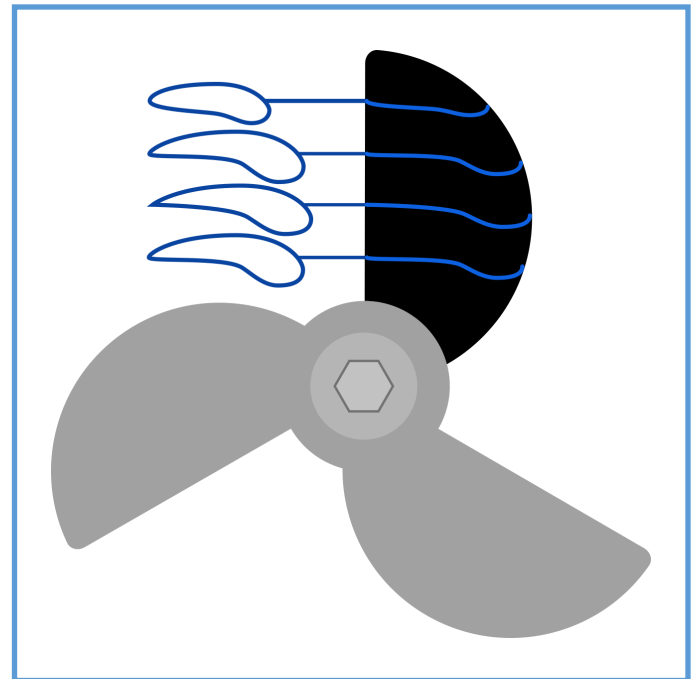
- [1] Guiard, T., Leonard, S., & Mewis, F. (2013). The Becker Mewis Duct® – Challenges in Full-Scale Design and new Developments for Fast Ships. *Third International Symposium on Marine Propulsors*. Retrieved from: <http://www.friedrich-mewis.de/files/Mewis/Publications/48.pdf>
- [2] Mewis, F., & Guiard, T. (2011). Mewis Duct® – New Developments, Solutions and Conclusions. *Second International Symposium on Marine Propulsors*. Retrieved from: http://www.marinepropulsors.com/smp/files/downloads/smp11/Paper/WA3-2_Mewis.pdf
- [3] Minchev, A., Schmidt, M., & Schnack, S. (2013). *The Becker Mewis Duct® – Challenges in Full-Scale Design and new Developments for Fast Ships. Third International Symposium on Marine Propulsors*. Retrieved from: https://www.researchgate.net/publication/261002250_Reducing_underwater_noise_from_large_commercial_ships_Current_status_and_future_directions
- [4] Becker Marine Systems (n.d) Retrieved from: <https://www.becker-marine-systems.com/products/product-detail/becker-mewis-duct.html>



New Blade Section Propellers

Overview:

Propeller blades experience differing forces down their length as they rotate. If the cross section of the blade is not optimized for these forces at various distances from the propeller hub, it can lead to irregularities in performance which can cause cavitation and a loss of efficiency. Optimizing the sections of the blade for these differing flow characteristics results in a more efficient vessel with a higher cavitation inception speed. For best results the propeller sections and hull shape should be optimized in tandem in order to ensure that they complement each other.



Cost

Little data was available on the cost of section optimization. However, Vesting, Bensow, Johansson, Gustafsson, and Costa note that the automated method which they investigated reduced the time investment, "by a factor of five," relative to traditional propeller design practices without compromising quality [1].

Noise Reduction

Optimization of propeller sections significantly improved the cavitation behavior of propellers, however noise was not directly measured. Further (preferably full-scale) testing is required [1][2].

Market Availability

Propeller optimization is already a standard industry practice. In addition, the algorithms used by Vesting et al to assemble their automated process were taken from the design toolbox of the Rolls Royce Hydrodynamic Research Center [1].

Efficiency Impact

Gains in propulsive efficiency of 1-3% were predicted in computational modeling of new blade section propellers [1].

Implementation

It is possible to add an optimized propeller to an existing ship. However, this requires extensive modeling to ensure compatibility, and best results are achieved from designing the propeller and hull in tandem [1].

Additional Maintenance

No additional maintenance tasks are created, as the changes to the propeller are not drastic enough to necessitate special upkeep or complicate regular cleaning.

References:

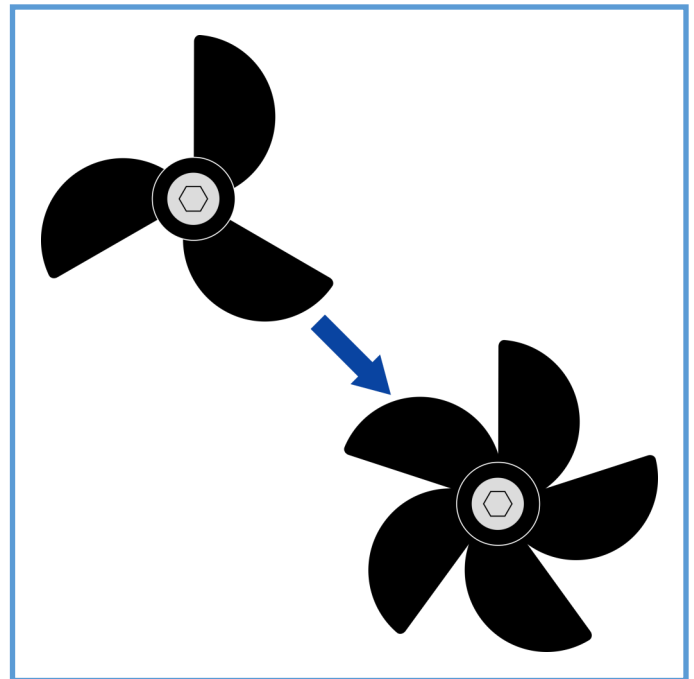
- [1] Vesting, F., Bensow, R., Johansson, R., Gustafsson, R., & Costa, N. (2016). Procedure for Application-Oriented Optimisation of Marine Propellers. *Journal of Marine Science & Engineering*, 4(83). DOI: 10.3390/jmse4040083
- [2] Zeng, Z., & Kuiper, G. (2011). Blade section design of marine propellers with maximum cavitation inception speed. *Journal of Hydrodynamics*, 24(1):64-75. DOI: 10.1016/S1001-6058(11)60220-5



Number of Propeller Blades

Overview:

Increasing the number of propeller blades is an effective solution for reducing propeller sheet cavitation and vibrations. Resonance effects between the propeller, hull, and machinery can cause unwanted vibrations, and increasing the blade count is a method to create a difference in frequencies. Naval ships generally have a higher blade count than traditional commercial ships for the purpose of reducing their vibrations, some testing more than 7 blades. For fixed pitch propellers, blade count is an independent parameter and is generally optimized to create the frequency imbalance between the propeller, hull, and machinery. It was found that propeller efficiency decreases as the number of blades is increased [1]. Implementing new propellers should generally be considered for new builds only, as existing vessels are already equipped with a propeller optimized for their build.



Cost

There are no available cost estimates for purchase or installation. Increasing the number of blades will likely increase cost because of the additional props required. The installation fee may slightly increase, as increasing the number of props will not change installation procedures but only the labor time.

Noise Reduction

Increasing the number of props is done for the purpose of reducing vibrations. The propeller can often create frequencies that resonate with the hull structure and machinery, and increasing the number of props can avoid this resonance affect. Sheet cavitation can also be limited by increasing the number of blades, because the total load is distributed over more blades [1].

Market Availability

The availability of increasing the number of propeller blades will be determined by material and labor availability. The number of propeller props is already a design parameter for new builds to determine maximum efficiency for a particular operating profile.

Efficiency Impact

Propeller efficiency and optimum propeller diameter increase as the number of blades decrease [1]. The three-bladed propeller has been proven to have the best balance, blade area, and efficiency. If reduced vibrations and resonant effects is an important goal, increasing the number of blades can be an effective solution.

Implementation

Increasing the number of propeller blades should only be considered for new builds. Existing vessel's propellers are already designed for their operating profile, and would require computational and model testing to retrofit a newly designed propeller. Typically merchant ships have 4-6 bladed propellers [1].

Additional Maintenance

There is little to no risk of additional maintenance for a propeller with more props. There will, however, be more surface area to clean, as well as more potential props to replace due to material erosion.

References:

- [1] Carlton, JS. (2007). Marine Propellers & Propulsion, Butterworth-Heinemann, (second edition) ISBN 978-07506-8150-6.
- [2] GetFPV. (2018). [Different number of prop configurations] [JPEG]. Retrieved from <https://www.getfpv.com/learn/new-to-fpv/all-about-multirotor-fpv-drone-propellers/>



Optimization of Engine Foundation

Overview:

Optimizing the main engine foundation can be an inexpensive alternative for new vessels to reduce their engine noise. The amount of underwater radiated noise by the engine is proportional to the dynamic stiffness of its foundation [1]. It is possible to apply empirical and finite element analysis to optimize the stiffness of the foundation to decrease the amount of underwater noise induced by the engine. This is commonly done by adding reinforcements to make the foundation stiffer. Optimizing the engine foundation may not be a significant strategy for commercial vessels because at design speed propeller cavitation will dominate machinery noise.



Cost

There are no available cost estimates for optimizing the main engine foundation. If the engine foundation is optimized during initial vessel design it will have little impact on the cost of the ship [1]

Noise Reduction

A study on the engine foundation of a passenger vessel found that for both of the foundation reinforcements tested, a noise reduction of 5 - 10 dB was achieved for frequencies above 100 Hz [1].

Market Availability

The tools necessary to optimize the engine foundation are commercially available. Simplified empirical and finite element methods are used to analyze the engine foundations [1].

Efficiency Impact

No significant impact on fuel efficiency due to a minor weight increase of the engine foundation. The estimated added weight is 0.3% to 0.7% of the total vessels displacement [1].

Implementation

Optimization of the engine foundation should only be considered for new builds. The cost to modify existing vessels would be too high to justify the potential noise reduction.

Additional Maintenance

There is expected to be no additional maintenance when reinforcing the engine foundation.

References:

- [1] AQUO (Achieve Quieter Oceans). (2015). Guidelines for regulation on UW noise from commercial shipping. FP7- Grant Agreement No. 314394. SONIC Deliverable 5.4



Podded Propulsion

Overview:

Podded propulsion is commonly paired with a diesel-electric engine housed in a compact pod. A fixed pitch propeller is located on top of the propeller shaft. Podded propulsion creates maneuverability in all directions by producing thrust in both the forward and aft directions. This method creates a uniform wake flow to the propeller, reducing cavitation and noise. Podded propulsion is commonly seen on ferries, cruise ships, and other passenger vessels [1]. This form of propulsion is not suitable for retrofit due to the extensive modifications that would be required. It is recommended that podded propulsion be incorporated into new build designs [2].

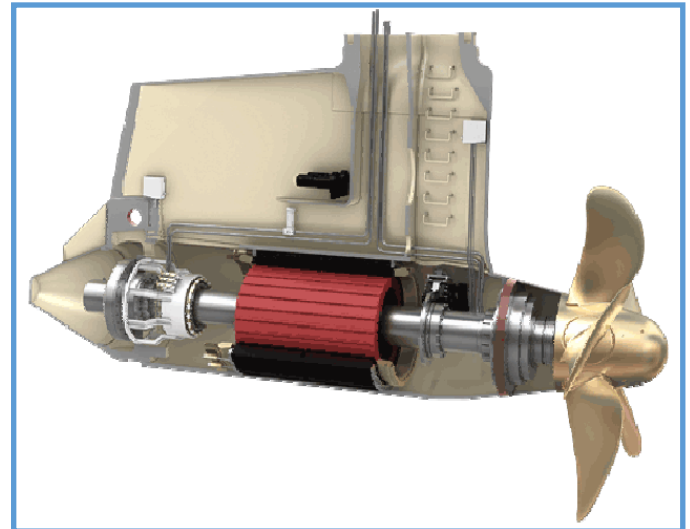


Image from [1]

Cost

The exact cost of podded propulsion is unavailable, but there is a high investment cost associated. There is also a risk of high maintenance costs for podded propulsion [1].

Noise Reduction

Podded propulsion can create a near-perfect uniform wake to the propeller, reducing cavitation and increasing efficiency, which can decrease noise. Noise reduction does not occur at all frequencies with podded propulsion, however. High noise levels can be generated at low frequencies due to the motor [1].

Market Availability

Podded propulsion is commercially available and has been installed on ferries and cruise ships, possibly due to its ability to reduce noise and create a more comfortable voyage for the ships passengers [1].

Efficiency Impact

Podded propulsion can achieve a 15-25% increase in hydrodynamic efficiency. It can also increase fuel efficiency up to 10%. A study found that to reach design speed on a roll-on/roll-off passenger vessel and a cargo ship, 20% less power was required while using a podded propulsion system [2].

Implementation

Podded propulsion is not suitable for retrofit due to extensive changes that would need to be made to the ship. It is recommended that this method be incorporated in new build designs [1]. Podded propulsion has been implemented on ferries, cruise ships, and warships. [1].

Additional Maintenance

There is a risk of high maintenance for podded propulsion.

References:

- [1] AQUO Consortium. (2015). *D5.1: Comprehensive listing of possible improvement solutions and mitigation measures [PDF file]*. Retrieved from http://www.aquo.eu/downloads/AQUO_R5_9_List_Mitigation_Measures_rev1_0.pdf
- [2] AQUO Consortium. (2015). *D5.5: Impact of Solutions on Fuel Efficiency [PDF file]*. Retrieved from http://www.aquo.eu/downloads/AQUO_D5.5_Impact_Fuel_Efficiency_rev1.0.pdf



Rudder Fins

Overview:

Rudder fins are paired hydrofoils extending from the rudder and attached at a point in line with the propeller shaft axis. A single pair may be mounted horizontally, or a larger even number of fins may be spaced evenly around the axis in a ring. They operate on the same principle as twisted rudders, recapturing lost energy from the propeller vortex and converting it into thrust. It is possible to combine rudder fins with other rudder upgrades (including propulsion bulbs and twisted rudders). As with twisted rudders they rely on the propeller vortex to function, so they are not compatible with vortex-reducing features such as propeller boss cap fins.

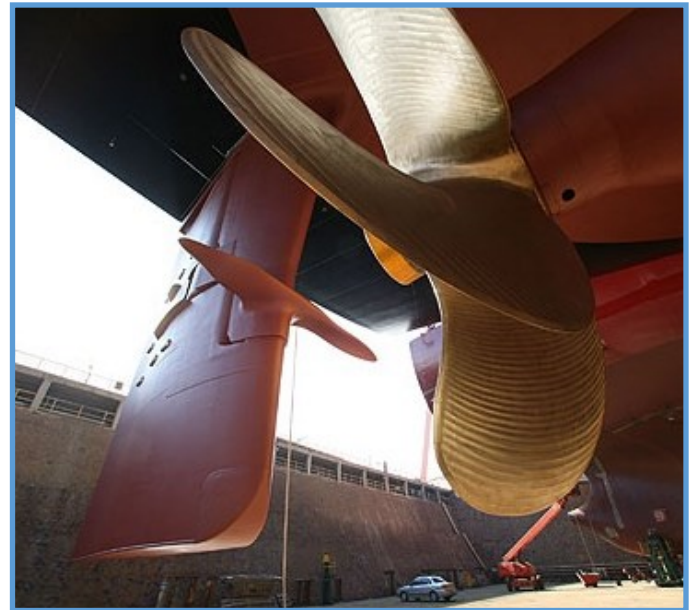


Image from [1]

Cost

Exact data were not available, however it is to be assumed that CFD modelling would be required to produce an optimal set of rudder fins for a given ship.

Noise Reduction

No direct link exists between the use of rudder fins and noise reduction. However, due to their efficiency benefits, they may offer an indirect benefit by reducing propeller load.

Market Availability

Available as part of a bulb system [2] or as a stand-alone upgrade [1].

Efficiency Impact

Kim, Choi, Choi, & Chung calculated that rudder fins, when used in conjunction with a propulsion bulb and twisted rudder, improved ship efficiency by 2.95% [3]. Manufacturer Hyundai Heavy Industries claimed a fuel savings of 5% in sea trials [1].

Implementation

Depending on the particular ship's existing rudder structure, adding rudder fins could involve alterations to the rudder horn or replacing the rudder entirely, as well as CFD modeling for optimization.

Additional Maintenance

Especially complex arrangements of rudder fins may increase the complexity of cleaning operations, but should not introduce any other new maintenance tasks.

References:

- [1] Hyundai Heavy Industries (2008). Thrust Fin Reduces Fuel Costs by More Than Five Percent. *World Shipping Directory*. Retrieved from: <http://www.ship.gr/news4/hyundai2.htm>
- [2] Kawasaki Heavy Industries Ltd. (2013). Bulk Carrier Global Venus Delivered. Retrieved from: http://global.kawasaki.com/en/corp/newsroom/news/detail/?f=20130401_1100
- [3] Kim, J.H., Choi, J.E., Choi, B.J., & Chung, S.H. (2014). Twisted rudder for reducing fuel-oil consumption. *International Journal of Naval Architecture & Ocean Engineering*, 6(715-722). DOI: 10.2478/IJNAOE-2013-0207



Schneekluth Duct

Overview:

The Schneekluth Duct, also known as the wake equalizing duct, was made to change the upstream flow from the propeller, aiming for a reduction of the radiated noise from the propeller's trailing edge. With a payback period of about four months because of its 12% decrease in fuel consumption, this makes it a good start to improving vessel efficiency and reducing acoustic pollution. The benefits of the wake equalizing duct is most seen if wake is originally not uniform [2]).



Image from [3]

Cost

"The total cost of the duct and associated spoilers for a 22-23 knot 2,500 TEU container ship is approximately \$120k, with the installation cost (during a scheduled dry dock) being about \$20k." It is also possible to save about 1,200 tons of annual fuel, which may result in a payback period in as few as four months [2].

Noise Reduction

Even though there appears to be insufficient data regarding its value as a practical method to reduce noise, a decrease of up to 50% vibration can be reached [1].

Market Availability

The Schneekluth Duct is commercially available. According to Renilson Marine Consulting, there have been a number of examples where the duct has been successfully fitted to existing ships [2]

Efficiency Impact

When the wake equalizing duct is installed on the hull, it can improve fuel consumption up to 12% [1].

Implementation

There have been many examples of successful fittings onto both existing and new vessels. Installing the duct can be done during a regular dry docking period and only takes a few days [2].

Additional Maintenance

There is minimum risk of increased maintenance, but there will be extra surfaces to clean during regular upkeep.

References:

- [1] Chekab, M. A. (2013). Investigation of Different Methods of Noise Reduction for Submerged Marine Propellers and Their Classification. *American Journal of Mechanical Engineering, Vol. 1 (No. 2)*. Retrieved from: https://www.researchgate.net/publication/275515444_Investigation_of_Different_Methods_of_Noise_Reduction_for_Submerged_Marine_Propellers_and_Their_Classification
- [2] Renilson Marine Consulting Pty Ltd. (2009.). *REDUCING UNDERWATER NOISE POLLUTION FROM LARGE COMMERCIAL VESSELS*[PDF]. Retrieved from: <http://ifaw-pantheon.s3.amazonaws.com/sites/default/files/legacy/Reducing%20Underwater%20Noise%20Pollutions%20for%20Large%20Commercial%20Vessels.pdf>
- [3] Schneekluth Hydrodynamik (n.d.) Retrieved from: <http://www.schneekluth.com/de/index.php>



Twisted Rudder

Overview:

One source of drag for a ship is the interaction between the rudder and propeller vortex. The rudder experiences uneven forces down its length as a result of the rotation of the vortex. In total these forces create drag. Twisted rudders alter the leading edge of the rudder so that it is angled into the vortex. The altered angle of attack allows the rudder to capture waste energy from the vortex, actually generating additional thrust as opposed to drag. Cavitation against the rudder is also reduced or eliminated. It is important to note that this feature requires a strong propeller vortex to function. Features such as Propeller Boss Cap Fins which reduce the vortex work at cross-purposes with twisted rudders.

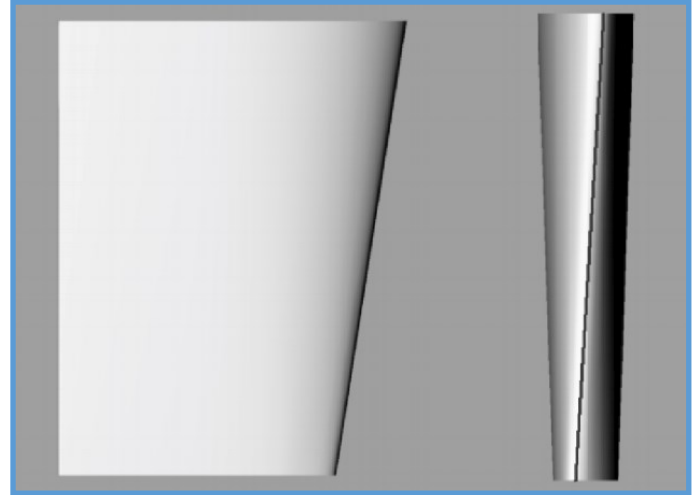


Image from [1]

Cost

Exact data were not available. However in an interview Becker Marine Systems Managing Director Dirk Lehmann highlighted the need for CFD modeling and additional propeller/rudder optimization work [2].

Noise Reduction

Manufacturer Becker Marine Systems claims that its twisted rudders reduce cavitation noise, but did not provide concrete numbers [2]. Ahn, Choi, Son, & Rhee discovered that a continuously twisted rudder displayed improved cavitation behavior and delayed cavitation inception [1].

Market Availability

Twisted rudders are currently on the market, and have been in use on commercial vessels since 2008 or earlier [3].

Efficiency Impact

Kim, Choi, Choi, & Chung predicted an efficiency gain of 2.35% with a twisted rudder (2014), similar to one distributor's claim of a 2% improvement [3].

Implementation

Adding a twisted rudder to an existing ship requires additional CFD modelling to ensure compatibility [2]. Additionally, some ships may require removal of the existing rudder horn in order to accommodate a twisted rudder.

Additional Maintenance

No additional maintenance tasks are created, as the changes to the rudder shape are not drastic enough to necessitate special upkeep or complicate regular cleaning.

References:

- [1] Ahn, K., Choi, G.H., Son, D.I., & Rhee, K.P. (2012). Hydrodynamic characteristics of X-Twisted rudder for large container vessels. *International Journal of Naval Architecture & Ocean Engineering*, 4(322-334). DOI: 10.2478/IJNAOE-2013-0100
- [2] "Becker Marine Brings 'Cross Over Rudder' Innovation". (2014). *World Maritime News*. <https://worldmaritimenews.com/archives/107636/becker-marine-brings-cross-over-rudder-innovation/>.
- [3] Nakashima Propeller Company, Ltd. (n.d.) Product Lineups, Other Marine Equipment: Rudders. Retrieved from: <https://www.nakashima.co.jp/eng/product/rudder.html>



Waterjet Propulsion

Overview:

Waterjet propulsion is an alternate form of propulsion that uses an impeller housed inside the hull and uses an internal pump to draw in water through a ducting system. The internal pump adds energy to the water, then expelling it at a high velocity. This alternate form of propulsion has potential to reduce noise, but at the cost of decreasing efficiency as well. Waterjet propulsion systems are heavier than those of conventional propellers, so it is recommended that they are best used on larger vessels [2].

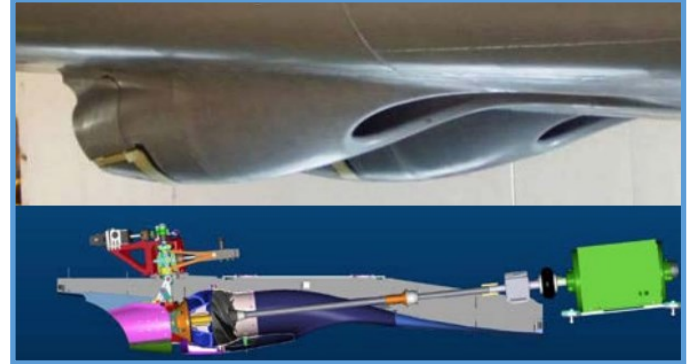


Image from [2]

Cost

Information on the cost of waterjets is not readily accessible. Designing a new build with waterjet propulsion could cost less than retrofitting a ship.

Noise Reduction

Waterjet propulsion consists of an impeller housed inside the hull. This can reduce the radiated noise from on-board machinery inside the hull. Because the impeller is house inside the hull, the pressure at the impeller is kept higher, reducing cavitation, therefore reducing noise [1].

Market Availability

Waterjet propulsion is commercially available.

Efficiency Impact

Waterjet pump efficiency has been reported to be 2% lower than conventional propulsion due to the system's weight [2]. The efficiency for high speed vessels using waterjet propulsion can be greater than those with open propulsion. Waterjet propulsion is not viable for commercial vessel from an efficiency standpoint [1].

Implementation

Waterjet propulsion is best implemented on new ships due to the hull design requirements. Waterjet propulsion would be best implemented on larger vessels, such as large wave-piercing ferries, because of the system's increased weight [2].

Additional Maintenance

Information regarding maintenance for waterjet propulsion is not available. Little to no additional maintenance can be expected due to waterjet propulsion using an impeller rather than a propeller.

References:

- [1] AQUO Consortium. (2015). *D5.5: Impact of Solutions on Fuel Efficiency [PDF file]*. Retrieved from http://www.aquo.eu/downloads/AQUO_D5.5_Impact_Fuel_Efficiency_rev1.0.pdf
- [2] ITTC Propulsion Committee. (2014). The Propulsion Committee. Retrieved from https://itc.info/media/6065/4-27th_propulsion_committee_report-new.pdf



Operational Practices

Contents:

Hull Cleaning

Operational Speed Reduction

Propeller Cleaning



Hull Cleaning

Overview:

Hull cleaning provides an immediate reduction to the noise generated from commercial vessels. Removing biofouling on the ship is already widely used to help increase ship efficiency by reducing hull drag. Reducing the amount of drag requires less output power which decreases the amount of noise generated. This also has the benefit of reducing propeller cavitation [2][3], and turbulence [1]. This operation must be performed while the ship is dry-docked or anchored and done many times. This is done in conjunction with antifouling paints, which also reduce drag. Although they degrade over time and are subject to increasing regulatory scrutiny due to toxic compounds, they are proven to have a significant effect on fuel efficiency. This method can be applied to any ship, making it a simple and effective solution for reducing noise and gradually saving on fuel costs [1].



Cost

The cost of hull cleaning varies depending on ship size, and cleaning method. Hull cleaning divers or robots can cost \$1.5-2/m² in the Far East, or \$50,000 USD to clean all areas of a very large crude carrier [1]. Savings on fuel can be expected due to the increase in fuel efficiency.

Noise Reduction

Hull cleaning is an effective solution that has the potential to reduce noise. Biofouling on the ship's hull creates a rough surface, increasing the drag experienced by the ship and necessitating higher engine output. Removing this biofouling through hull cleaning can eliminate these effects and reduce underwater noise [1].

Market Availability

Hull cleaning is available for all existing ships. This can be done by divers or hull cleaning robots while the ship is dry-docked or anchored [1].

Efficiency Impact

Overall ship efficiency has seen to increase after cleaning the hull. Hull cleaning increases efficiency through reducing biofouling on the hull, reducing the resistance experienced up to 50%. Hull cleaning can decrease fuel consumption between 7-30% [1].

Implementation

Hull cleaning can be done on all existing ships while they are dry-docked or anchored [1]. Hull maintenance and cleaning on existing ships is important in reducing ship noise and increasing efficiency

Additional Maintenance

There is no to little risk of additional maintenance with hull cleaning. This method must be done frequently to remove the biofoul on the hull's surface.

References:

- [1] AQUO Consortium. (2015). *D5.1: Comprehensive listing of possible improvement solutions and mitigation measures [PDF file]*. Retrieved from http://www.aquo.eu/downloads/AQUO_R5_9_List_Mitigation_Measures_rev1_0.pdf
- [2] Hemmera Envirochem Inc. (2016). *Vessel Quieting Design, Technology, and Maintenance Options for Potential Inclusion in EcoAction Program Enhancing Cetacean Habitat and Observation Program [PDF file]*. Retrieved from <https://www.portvancouver.com/wp-content/uploads/2017/01/Vessel-Quieting.pdf>
- [3] International Maritime Organization. (2014). *Guidelines For the Reduction of Underwater Noise From Commercial Shipping to Address Adverse Impacts on Marine Life [PDF file]*. Retrieved from https://www.nrdc.org/sites/default/files/wat_14050501a.pdf



Operational Speed Reduction

Overview:

Reducing the speed at which a vessel operates is an immediate method that can reduce noise, save fuel, and increase efficiency. Operating the ship below or close to the propeller's cavitation inception speed will eliminate cavitation effects and the noise it generates. A slower operating speed reduces the resistance experienced by the ship, decreasing the amount of power needed to move the vessel. This reduces fuel consumption and can generate large cost savings. Although operating at a lower speed can reduce noise and increase fuel efficiency, these savings may be offset by the fact that the onboard machinery is not optimized to operate at such low speeds, and longer voyages require extended crewing pay, among other economic factors. Therefore, it may be impractical for some commercial vessels to operate under such low speeds [1].



Image from [2]

Cost

Speed reduction can generate a significant increase in cost savings due to the fuel efficiency of the ship increasing. These savings could potentially be offset due to the increased voyage time and extended pay of crew members, along with other economic factors [1].

Noise Reduction

Travelling at a slower speed can significantly decrease noise. Moving at a decreased speed reduces the amount of engine power needed, which can decrease onboard machinery noise. Running the propeller close to or below the cavitation inception speed can eliminate the effects of cavitation, including noise [1].

Market Availability

Speed reduction is available for all existing ships.

Efficiency Impact

Speed reduction decreases the resistance experienced by the ship, which lowers the power required to run the engine. This reduces fuel consumption, which increases the fuel efficiency of the ship. Reducing a ship's speed by 20% can reduce fuel consumption by 50% [1].

Implementation

While travelling at reduced speeds can have many benefits, it is not practical for most commercial ships to operate at low speeds under normal operating conditions [1].

Additional Maintenance

There is no to little additional maintenance required when reducing a ship's operational speed.

References:

- [1] AQUO Consortium. (2015). *D5.5: Impact of Solutions on Fuel Efficiency [PDF file]*. Retrieved from http://www.aquo.eu/downloads/AQUO_D5.5_Impact_Fuel_Efficiency_rev1.0.pdf
- [2] Vineyard, J. (2018, February 09). Slow Steaming (SS) or Super Slow Steaming (SSS) for Container Shipping Part I. Retrieved from <https://www.universalcargo.com/slow-steaming-ss-or-super-slow-steaming-sss-for-container-shipping-part-i/>



Propeller Cleaning

Overview:

Propeller cleaning provides an immediate reduction to the noise generated from commercial vessels. Removing biofouling on the ship is already widely used to help increase ship efficiency by reducing propeller drag. Reducing the amount of drag requires less output power which decreases the amount of noise generated. This also has the benefit of reducing propeller cavitation [3][4], and turbulence [1][2]. Propeller cleaning must be performed while the ship is dry-docked or anchored and done many times. This method can be applied to any ship, making it a simple and effective solution for reducing noise and gradually saving on fuel costs [1].



Cost

The cost of propeller cleaning depends on the propeller's diameter, number of blades, and the amount of time will take to clean. In the Far East, to clean a 5 blade propeller with a 10 meter diameter, it takes 3 to 4 hours and costs about \$3000 USD [1]. Savings on fuel can be expected due to the increase in fuel efficiency, outweighing the cost of propeller cleaning, and making the ship less costly overall.

Noise Reduction

Propeller cleaning is a highly effective method to reduce noise [3]. There is a significant reduction in propeller cavitation and turbulence, which can lead to a decrease in noise from the propeller [2][3].

Market Availability

Propeller cleaning is available to be done on existing ships. This can be done underwater by divers while the ship is in dry-dock [1].

Efficiency Impact

Overall ship efficiency has seen to increase after cleaning the propeller. Propeller cavitation and turbulence is reduces, increasing efficiency [3]. Propeller cleaning can decrease fuel consumption up to 6% [1].

Implementation

Propeller cleaning can be done on all existing ships while they are dry-docked or anchored [1]. Propeller maintenance and cleaning on existing ships is important in reducing ship noise and increasing efficiency.

Additional Maintenance

There is no to little risk of additional maintenance when propeller cleaning. This method must be done frequently to remove the biofoul on the propeller's surface.

References:

- [1] AQUO Consortium. (2015). *D5.1: Comprehensive listing of possible improvement solutions and mitigation measures [PDF file]*. Retrieved from http://www.aquo.eu/downloads/AQUO_R5_9_List_Mitigation_Measures_rev1_0.pdf
- [2] AQUO Consortium. (2015). *D5.5: Impact of Solutions on Fuel Efficiency [PDF file]*. Retrieved from http://www.aquo.eu/downloads/AQUO_D5.5_Impact_Fuel_Efficiency_rev1.0.pdf
- [3] Hemmera Envirochem Inc. (2016). *Vessel Quieting Design, Technology, and Maintenance Options for Potential Inclusion in EcoAction Program Enhancing Cetacean Habitat and Observation Program [PDF file]*. Retrieved from <https://www.portvancouver.com/wp-content/uploads/2017/01/Vessel-Quieting.pdf>
- [4] International Maritime Organization. (2014). *Guidelines For the Reduction of Underwater Noise From Commercial Shipping to Address Adverse Impacts on Marine Life [PDF file]*. Retrieved from https://www.nrdc.org/sites/default/files/wat_14050501a.pdf



Additional Technologies

Contents:

Acoustic Enclosures

Active Insulation

Air Bubble Curtain

Anti-Fouling Paints

Biomimetic Coatings

Elastic Mounting

Grothues Spoilers

Pre-Swirl Stators

Propeller Boss Cap Fins & Propeller Cap Turbines

Simplified Compensative Nozzle

Vortex Generator



Acoustic Enclosures

Overview:

Acoustic enclosures are designed to isolate and dampen airborne noise from on board machinery. They are closed systems made from sound dampening material. Although traditionally used to reduce airborne noise for the purpose of human safety, their benefits can extend to underwater noise. Within the maritime industry, acoustic enclosures see the most use on naval ships, cruise liners, and luxury yachts. Some manufacturers have also designed acoustic enclosures to have vibration insulating capabilities, which can improve underwater radiated noise from induced hull vibrations.



Image from [1]

Cost

Price will vary depending on the amount of dampening required and the application of the enclosure. Estimated cost of sound dampening material is \$1-4 per square feet of material [3].

Noise Reduction

No studies showing any measurable noise reduction. An Australian manufacturer claims their acoustic enclosures can reduce the machinery noise by 15 - 50 dBA [2].

Market Availability

There are numerous manufacturers producing acoustic enclosures and sound dampening material for industrial use. Sonic-Shield is a US based company that specializes in acoustic dampening and acknowledges underwater noise pollution.

Efficiency Impact

Research has shown no significant impact on operational efficiency. The small weight of acoustic enclosures compared to the overall ship mass will likely cause no impact on fuel efficiency.

Implementation

Acoustic enclosures can be implemented on existing vessels and new builds. Depending on the noise reduction required, acoustic enclosures can also be designed to include vibration insulation.

Additional Maintenance

Expected to add little to no additional maintenance. Acoustic enclosures can be made modular which allows for easier maintainability.

References:

- [1] [An acoustic enclosures for bow thrusters and generators]. (n.d.). Retrieved from <https://www.alaralukagro.com/en/project/soundproofing-for-bow-thrusters-and-generators/>
- [2] Noise Control Engineering (n.d). *Acoustic Enclosures*. <http://noisecontrolengineering.com.au/acoustic-enclosures-2/>
- [3] Southall, B. L. and A. Scholik-Schlomer. (2008). Final report of the NOAA International Conference: “Potential Application of Vessel-Quieting Technology on Large Commercial Vessels,” 1-2 May, 2007, Silver Spring, MD, U.S.A.



Active Insulation

Overview:

Active Insulation or Active Noise Control (ANC) is a form of sound dampening that utilizes a secondary source of sound to interfere with the primary source. Sound waves that interfere and are out of phase will have a canceling affect, known as destructive interference. This is the principal behind ANC. A secondary sound source in reverse phase to the primary noise is introduced into the system that will significantly cancel out the magnitude of the sound. This technology is widely used in noise-canceling headphones. Its application to ship engines is experimental, but the technology is showing great promise.

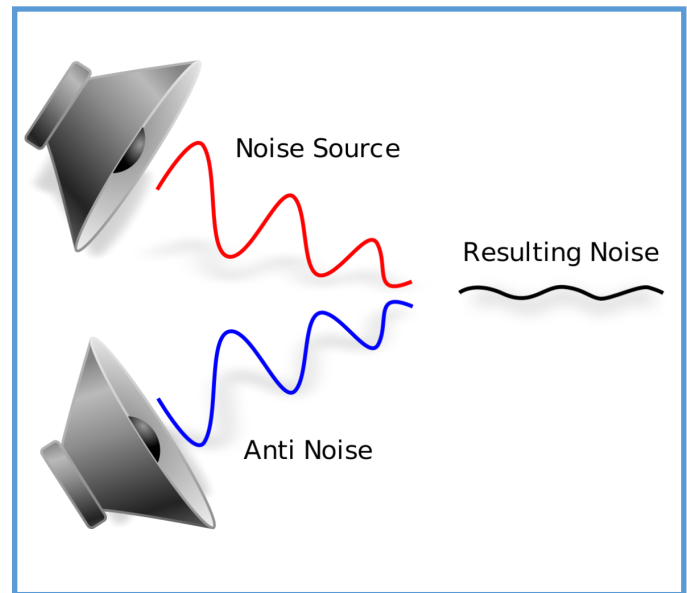


Image from [3]

Cost

The cost of implementing active insulation has been said to be too high for the commercial shipping industry to adopt [1]. To minimize cost, active insulation should be installed on new builds.

Noise Reduction

There have been experiments done using active noise control on vessel engines that showed single peak vibration reductions of 30 dB and an overall reduction of 8-10 dB [2]. Engines tested were MTU 2000 and 4000 series diesel.

Market Availability

Active insulation is commercially available, but the use of it for vessel engines is still being experimented. Other industrial active noise control may be able to be implemented inside an engine room with proper design consideration.

Efficiency Impact

There is no significant impact on fuel efficiency, because the weight of the insulation is negligible compared to total vessel weight [1]

Implementation

Active noise control should only be considered for new builds because the cost to retrofit is very high and there is no expected ROI. Implementing this during the design process will help keep costs down.

Additional Maintenance

There is expected to be additional maintenance because active insulation requires additional machinery mountings, sensors, controllers and actuators to operate [1].

References:

- [1] AQUO Consortium. (2015). *D5.5: Impact of Solutions on Fuel Efficiency [PDF file]*. Retrieved from http://www.aquo.eu/downloads/AQUO_D5.5_Impact_Fuel_Efficiency_rev1.0.pdf
- [2] Husick, C. (2009). *Quieting engine noise*. Retrieved from <http://www.oceannavigator.com/May-June-2009/Quieting-engine-noise/>
- [3] Marekich. (2012). Active Noise Reduction [PNG]. Retrieved from https://en.wikipedia.org/wiki/Active_noise_control#/media/File:Active_Noise_Reduction.svg



Air Bubble Curtain

Overview:

Bubble curtains are a technology that can be applied to the hull and propeller of ships to reduce the propagation of underwater noise. They produce bubbles that use the sound dampening properties of air to reduce noise from ships. Bubble curtains have been commonly used to reduce the underwater noise created by pile-driving [2]. Hull bubble curtains can act as an insulator, reducing the propagation of on-board machinery noise. They are most effective at medium to high frequencies. Propeller bubble curtains can dampen the noise created by propeller cavitation. These are most effective at low frequencies [1]. Bubble curtains cause a slight decrease in overall efficiency. It is recommended that bubble curtains only be incorporated into new build designs [2].

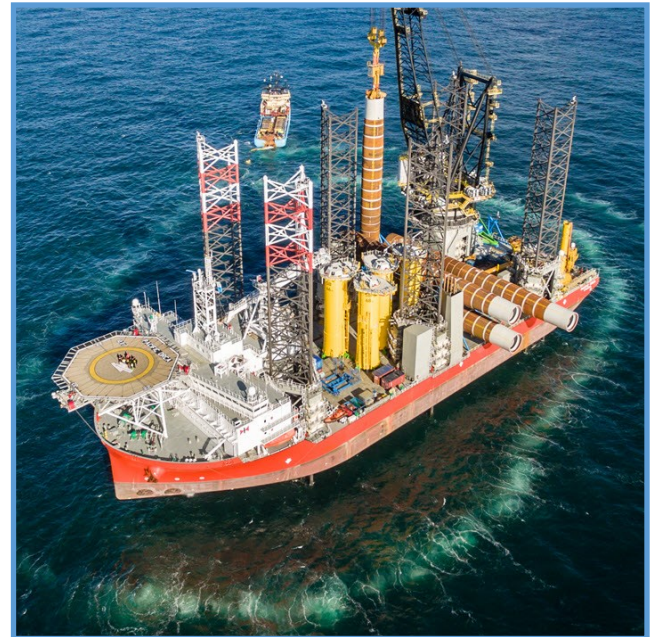


Image from [3]

Cost

While the cost of a bubble curtain is not readily available, retrofitting a ship with a bubble curtain requires major modifications to the ship and extensive dry-docking, which can be costly. Implementing a bubble curtain into new build designs would be less costly than a retrofit [2].

Noise Reduction

There is evidence that bubble curtains can reduce underwater noise. Hull bubble curtains are very effective in reducing noise at medium to high frequencies, while propeller bubble curtains are more effective in reducing noise at low frequencies. When combined, hull and propeller bubble curtains can achieve an overall noise reduction between 3 and 6 dB [1].

Market Availability

Bubble curtains are commercially available and are commonly used to reduce the propagation of underwater noise from pile-driving.

Efficiency Impact

Bubble curtains add a small amount of weight to vessels. They cause a 1% decrease in ship speed, and a 2% decrease in shaft power. There is little data regarding the effects on fuel efficiency, but a small decrease in fuel efficiency can be expected. Overall, a small decrease in efficiency can occur [2].

Implementation

It is not recommended to retrofit a ship with a bubble curtain. This requires extensive dry-docking to install pipes under the hull, and an on-board air compressor to generate bubbles. Bubble curtains would be best incorporated into newbuild designs [2].

Additional Maintenance

There is a risk of increased maintenance with bubble curtains. Adding an extra system to a ship can increase the amount of cleaning and repairs required.

References:

- [1] AQUO Consortium. (2015). *D5.3: Assessment of the solutions to reduce underwater radiated noise [PDF file]*. Retrieved from http://www.aquo.eu/downloads/AQUO_D5.3_Assessment_URN_reduction_rev1.0.pdf
- [2] AQUO Consortium. (2015). *D5.5: Impact of Solutions on Fuel Efficiency [PDF file]*. Retrieved from http://www.aquo.eu/downloads/AQUO_D5.5_Impact_Fuel_Efficiency_rev1.0.pdf
- [3] Jasica, M. (2018, June 19). Oil-free bubble curtains protecting marine life. Retrieved from <https://rentalcompressedairblog.com/oil-free-bubble-curtains-protecting-marine-life/>



Anti-Fouling Paints

Overview:

Anti-fouling paints come in many unique forms that reduce drag. Although tending to degrade and taint the immediately surrounding waters, it is proven to have a prominent effect to increase fuel efficiency over time [1]. Being able to be applied to any ship makes it a simple and effective solution for reducing noise and gradually saving on fuel costs



Cost

No cost estimates are available. Paint prices will increase moving from common, lesser quality paints to unique or special polymer coatings.

Noise Reduction

The fouling of barnacles and other sea organisms cause an overconsumption of fuel and increase in propeller speed. These paints reduce this fouling, increasing ship efficiency which correlates to reducing ship noise [1].

Market Availability

Anti-fouling paints are very prevalent in the market, however the majority of these types of paint contain polluting components as the paint degrades and breaks down [35].

Efficiency Impact

By eliminating biofouling on the hull, there is much less drag for the propeller to overcome. This results in a significant increase in fuel efficiency over time, and should be combined with another noise reducing method for optimal efficiency.

Implementation

Anti-fouling paints can be applied to both existing vessels and new builds without extra careful considerations or costly tests.

Additional Maintenance

There is likely to be minimal extra maintenance. Paints should be reapplied during regular dry dock periods to prolong its effectiveness [2].

References:

- [1] Cambon, C. (1995). *U.S. Patent No. US5717007A. Washington, DC: U.S. Patent and Trademark Office. Retrieved from: <https://patents.google.com/patent/US5717007A/en>*
- [2] Konstantinou, I. (2003, September 02). Worldwide occurrence and effects of antifouling paint booster biocides in the aquatic environment: A review. Retrieved from <https://www.sciencedirect.com/science/article/pii/S0160412003001764#BIB88>
- [3] Weidman, L. (2007). *U.S. Patent No. US20100015349A1. Washington, DC: U.S. Patent and Trademark Office. Retrieved from: <https://patents.google.com/patent/US20100015349A1/en>*



Biomimetic Coatings

Overview:

Biomimetic coatings are a collection of experimental and theoretical antifouling substances which mimic the structural, chemical, or other properties of marine life. Many organisms exhibit much lower levels of fouling on their bodies than would be expected. Approaches to mimic these properties include engineered nanoscale roughness to reduce spore adhesion, chemicals to repel live fouling organisms, and even counter-attacking live agents embedded in a paint matrix. While the field is still largely experimental, it is the subject of considerable research, and novel combinations of approaches continue to be developed.

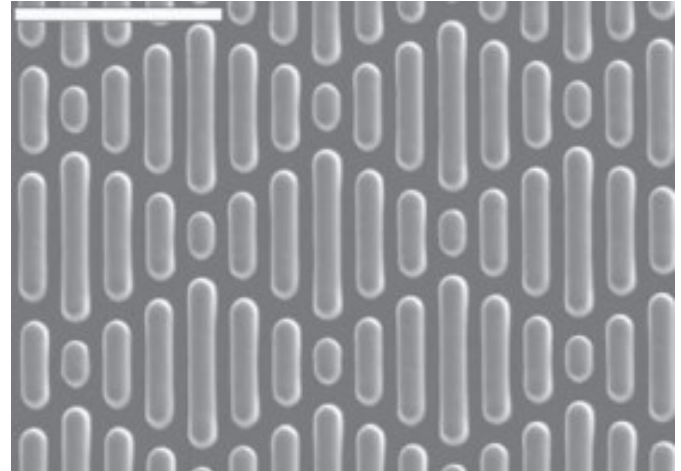


Image from [2]

Cost

As development is in the early stages, costs can vary. One distributor of Sharklet samples sells kits consisting of twelve two-inch sample disks for \$1,000 [1], while a University of Singapore group presented an invoice showing they were able to acquire film samples for \$0.00587 per square inch [5].

Noise Reduction

Experiments have so far focused on organism adhesion. A successful coating would reduce hull drag from biofouling, leading to less noise from turbulence, but experimental confirmation is still forthcoming.

Market Availability

One product, Sharklet antimicrobial film, is available for experimentation and production licensing [4].

Efficiency Impact

Antifouling impact is potentially significant, with one study showing that Sharklet film reduced marine spore settlement by 77% [2]. Exact impact on efficiency remains unknown, pending testing.

Implementation

Varies with the coating's properties. Applying film-form coatings to an entire ship could be highly work intensive, while spray-on coatings would involve no more work than applying current types of antifouling paint.

Additional Maintenance

Varies with the coating's properties. Current types have been shown to retain effectiveness for as little as a few weeks or as much as a year, but even the high end still falls short of the endurance required of current antifouling paints [3].

References:

- [1] 10x Microstructures (n.d.). Sharklet Technologies. Retrieved from: www.10xmicro.com/id87.htm
- [2] Callow, J., & Callow, M. (2011). Trends in the development of environmentally friendly fouling-resistant coatings. *Nature Communications*, 2(244). DOI: 10.1038/ncomms1251
- [3] Salta, M., Wharton, J., Stoodley, P., Dennington, S., Goodes, L., Werwinski, S., Mart, U., Wood, R., & Stokes, K. (2010). Designing biomimetic antifouling surfaces. *Philosophical Transactions of the Royal Society*, 368:4729-4754. DOI: 10.1098/rsta.2010.0195
- [4] Sappi North America (2016). Sappi North America Announces Neoterix™ST, the First Commercial Casting and Release Paper with Sharklet™ Bacteria-Inhibition Technology. *Cision PR News-wire*, September 12, 2016. Retrieved from: <https://www.prnewswire.com/news-releases/sappi-north-america-announces-neoterixst-the-first-commercial-casting-and-release-paper-with-sharklet-bacteria-inhibition-technology-300325590.html>
- [5] YiYiang, L., Wee, L.K., Rongbin, L., Yin, C.M., & Wei, L.K. (2014). MT5016 - Business Models for Hi-Tech Products. Presented by Jeffrey Funk, Associate Professor at National University of Singapore, November 17, 2014. Retrieved from: <https://www.slideshare.net/funk97/sharklet-bacteria-and-hospitals>



Elastic Mounting

Overview:

Elastic mounting for vessel engines is a proven solution used to reduce onboard engine noise. It works to insulate the vibrations induced by engine operation from radiating through the hull into the ocean. Elastic mounts cannot be used on traditional slow speed two-stroke diesel engines, because of the engine's weight. These mounts are used on smaller faster engines. It is important to optimize the stiffness of the mount and engine foundation to maximize noise reduction and avoid resonance effects.

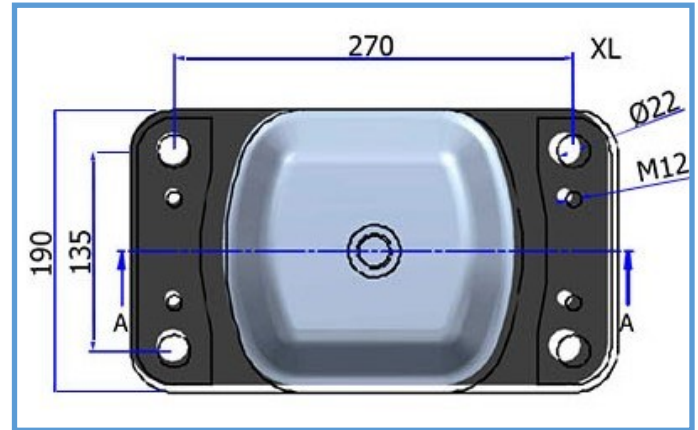


Image from [2]

Cost

No available purchase or installation cost estimates are available. Price will vary depending on which type of mount is required for the optimal stiffness to achieve maximum noise reduction.

Noise Reduction

The level of noise reduction for an elastically mounted medium speed engine can reach between 20-40 dB over the entire frequency range [1]. The noise levels were measured from above and below the elastic mounts.

Market Availability

Elastic mounts are commercially available and have proven to be efficient at reducing engine vibrations. There are multiple types of mounts on the market that range from vibration insulation to stability applications.

Efficiency Impact

There is no significant impact on fuel efficiency for single elastic bench mounts because their weight is insignificant compared to the total weight of the vessel. Double elastic bench mounts may impact fuel efficiency due to considerable mass.

Implementation

Elastic mounts cannot be used on vessels with two-stroke diesel engines. Elastic mounting can be implemented on new and existing vessels that use medium to high speed engines.

Additional Maintenance

There is expected to be minimal additional maintenance, but at least once during a vessel's lifetime the elastic mounts will have to be replaced due to material degradation.

References:

- [1] AQUO (Achieve Quieter Oceans). 2015. Guidelines for regulation on UW noise from commercial shipping. FP7- Grant Agreement No. 314394. SONIC Deliverable 5.4
- [2] AV Products, Inc. (n.d). MM XL [JPEG]. Retrieved from <https://www.avproductsinc.com/mobile-marine/mounts.html>



Grothues Spoilers

Overview:

Grothues spoilers are curved fins attached to the hull ahead the propeller. Their function is to straighten the flow of water to the propeller, which has shown to improve propeller efficiency. It is unknown their impact on underwater noise, but it is theorized that improving propeller flow could help reduce cavitation. Grothues spoilers should be designed carefully because they can increase ship drag if the flow of the ship is already relatively uniform [3]. Grothues spoilers are only applicable on single-screw vessels and perform best on moderately U-shaped hulls [5].

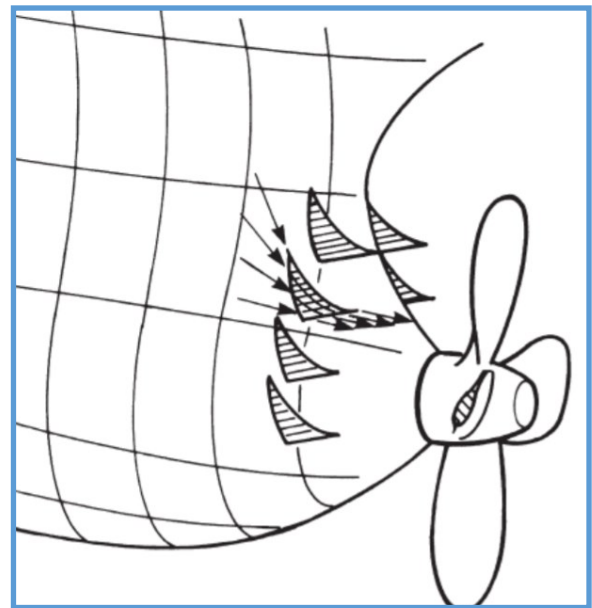


Image from [2]

Cost

There are no purchase or installation estimates available. In order to effectively utilize the flow improvements of Grothues spoilers hydrodynamic and mechanical design testing is required, which will add to the implementation costs.

Noise Reduction

No studies researched the relationship between underwater noise and the presence of Grothues spoilers. In theory improving the flow to the propeller can reduce the amount of cavitation, resulting in a reduction of underwater noise.

Market Availability

Grothues spoilers are commercially available. According to Schneekluth, only 35 were installed on ships up to 1991 [4]. This technology does not seem to be frequently used on current vessels.

Efficiency Impact

Propeller efficiency is claimed to be increased by 3-9% depending on the type of ship [1]. Tankers and bulk carries in ballast showed the greatest increase at 9% [3].

Implementation

Grothues Spoilers can be implemented on both existing vessels and new builds. It is advised to only consider new builds because of the required hydrodynamic and mechanical testing that needs to be done.

Additional Maintenance

There is expected to little to no risk of additional maintenance associated with using Grothues Spoilers. Normal operational upkeep can be expected with the attached fins.

References:

- [1] AQUO Consortium. (2015). *D5.5: Impact of Solutions on Fuel Efficiency [PDF file]*. Retrieved from http://www.aquo.eu/downloads/AQUO_D5.5_Impact_Fuel_Efficiency_rev1.0.pdf
- [2] Maritime Academy. (n.d). Grothues Spoilers [PNG]. Retrieved from https://www.ntnu.edu/documents/20587845/1266707380/02_EnergySaving_Hydrodynamics.pdf/50ff6d18-b3d4-4389-8f97-6a0a882e721f
- [3] Renilson Marine Consulting Pty Ltd. (2009.). *Reducing Underwater Noise Pollution From Large Commercial Vessels [PDF]*. Retrieved from: <http://ifaw-pantheon.s3.amazonaws.com/sites/default/files/legacy/Reducing%20Underwater%20Noise%20Pollutions%20for%20Large%20Commercial%20Vessels.pdf>
- [4] Schneekluth, H., & Bertram, V. (1998). *Ship Design for Efficiency and Economy*. Retrieved from http://www.mojaladja.com/upload/Profa/Dizajn_brodova.pdf
- [5] Quadvlieg, F. (2009). *Marine Propulsion and Fuel Economy [PDF file]*. Retrieved from http://www.aquo.eu/downloads/AQUO_D5.5_Impact_Fuel_Efficiency_rev1.0.pdf



Pre-Swirl Stators

Overview:

Pre-Swirl Stators are a technology that aims to recover rotational losses in a propeller slipstream. Stator fins are attached on the stern boss of the vessel in front of the propeller [2], to help improve the flow of the propeller. It is not known if this technology reduces underwater noise, but it does improve the flow to the propeller, which is linked to reducing noise. Stator fins should be considered for new builds only because of their complicated design and the required model testing. They do increase ship drag, but they also increase propulsive efficiency.

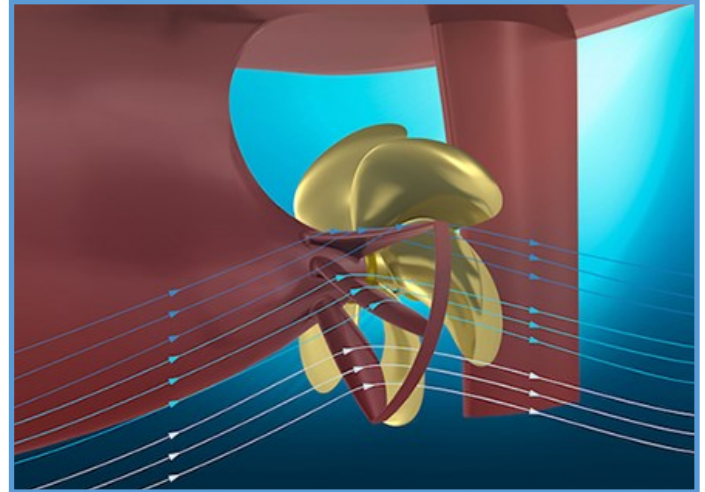


Image from [3]

Cost

There are no available estimates for purchase or installation. To optimize the stator fins, model testing will have to be done, which will add additional costs.

Noise Reduction

There was no evidence of noise reduction found. It is understood that improving the water flow to the propeller will reduce noise, but this has not been confirmed with pre-swirl stators.

Market Availability

Pre-swirl stators are commercially available. The manufacturer, Wartsila announced a new pre-swirl stator design in 2017, which shows market interest in the technology.

Efficiency Impact

Using pre-swirl stators have shown to increase propulsive efficiency by 4-6%, but with the cost of increased ship drag [1].

Implementation

This technology should only be considered for new vessel builds. They are difficult to retrofit because of the required model testing that is needed to ensure maximum performance.

Additional Maintenance

There is expected to be little to no additional maintenance because there are no moving parts. Regular upkeep of the fins is the only necessary maintenance.

References:

- [1] AQUO Consortium. (2015). *D5.5: Impact of Solutions on Fuel Efficiency [PDF file]*. Retrieved from http://www.aquo.eu/downloads/AQUO_D5.5_Impact_Fuel_Efficiency_rev1.0.pdf
- [2] FLOWTECH. (n.d). *Pre-Swirl Stator optimization [PDF file]*. Retrieved from https://www.flowtech.se/images/cases/_pdf/Leaflet_PSS_optimization.pdf
- [3] Wartsila Corporation. (2017). [Pre-swirl stator design] [JPEG]. Retrieved from <https://www.wartsila.com/media/news/07-11-2017-wartsila-introduces-an-innovative-pre-swirl-stator-to-improve-fuel-efficiency>



Propeller Boss Cap Fins & Propeller Cap Turbines

Overview:

Propeller boss cap fins and cap turbines are similar structures which can be attached to the boss of a propeller. They consist of a group of small fins equal to the number of blades on the propeller and mounted just aft of the blades. These fins alter the performance characteristics of the propeller boss, reducing the pressure differential which creates the propeller vortex. The difference between PBCF and PCT is rooted in fin shape: PBCF consist of flat plates with uniform cross-sections, while PCT consist of hydrofoils with variable cross-sections. Both systems exhibit comparable performance. Due to their reduction or elimination of the propeller vortex, PBCF/PCT are not compatible with some rudder upgrades.

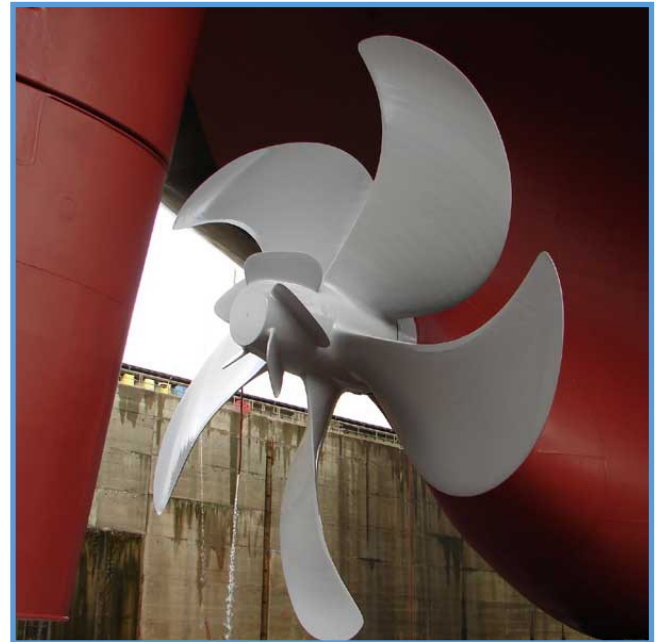


Image from [1]

Cost

Estimates based on time to payoff information provided by manufacturer Wartsila indicate a possible cost range of \$57,000 to \$114,000, with ROI within as little as a year [1][4]).

Noise Reduction

Gassman, Kindberg, Wiggins, & Hildebrand note that PBCF were one of the key upgrades in the Maersk G-Class retrofit program, and may have contributed strongly to reducing those ships' radiated noise by 6-8 dB [2].

Market Availability

Available from multiple manufacturers, some trading specifically in PBCF or PCT.

Efficiency Impact

Multiple manufacturers claim an efficiency improvement range from 3-5% [1][3] [4].

Implementation

Design requires some lead time for CFD modeling. Installation is rapid and can be carried out while the ship is still afloat, though it can be carried out more rapidly in drydock [1].

Additional Maintenance

Changes to overall propeller geometry are minimal, requiring only regular cleaning as part of normal ship maintenance.

References:

- [1] Fathom Shipping (2012). Propeller Technology to Make Your Ship More Efficient. *gCaptain*, July 17, 2012. Retrieved from: <https://gcaptain.com/propeller-technology-ship-efficient/>
- [2] Gassman, M., Kindberg, L., Wiggins, S., & Hildebrand, J. (2017). Underwater noise comparison of pre- and post-retrofitted MAERSK G-class vessels. Marine Physical Laboratory, Scripps Institute of Oceanography. Retrieved from: <http://cetus.ucsd.edu/Publications/Reports/GassmannMPLTM616-2017.pdf>
- [3] Mitsui O.S.K. Lines. (2015). Energy-Saving Propeller Boss Cap Fins System Reaches Major Milestone - Orders Received for 3,000 Vessels. Retrieved from: <https://www.mol.co.jp/en/pr/2015/15033.html>
- [4] Pospiech, P. (2013). Improved Propulsive Efficiency by Weaking the Propeller Hub Vortex. *Maritime Propulsion*. Retrieved from: <http://articles.maritimepropulsion.com/article/IMPROVED-PROPULSIVE-EFFICIENCY-BY-WEAKING-THE-PROPELLER-HUB-VORTEX84713.aspx>



Simplified Compensative Nozzle

Overview:

The Simplified Compensative Nozzle is installed on both sides of the hull in the aft section. It is designed to optimize the uniformity of the inflow to the propeller. Its unique vertical shape helps to improve flow, as well as simplifying its production.



Image from [2]

Cost

The Simplified Compensative Nozzle can be built much easier in comparison to other wake inflow modification tools, and fabrication costs are also reduced due to its simple manufacturing process [1][2].

Noise Reduction

The Simplified Compensative Nozzle aims to homogenize the wake inflow in the stern region. This results in a decrease of noise due to the propeller's reduced inflow oscillations [1].

Market Availability

These are commercially available, however this technology does not appear to be used frequently.

Efficiency Impact

A vertical shape, rather than a typical circular shape, refines uniformity of wake flow into the propeller, improving overall propeller efficiency [2]

Implementation

This add-on can be implemented on both new and existing vessels, however hydrodynamic and mechanical testing should be done to ensure optimal efficiency levels.

Additional Maintenance

There is expected to be little to no risk of additional maintenance with the addition of a Simplified Compensative Nozzle.

References:

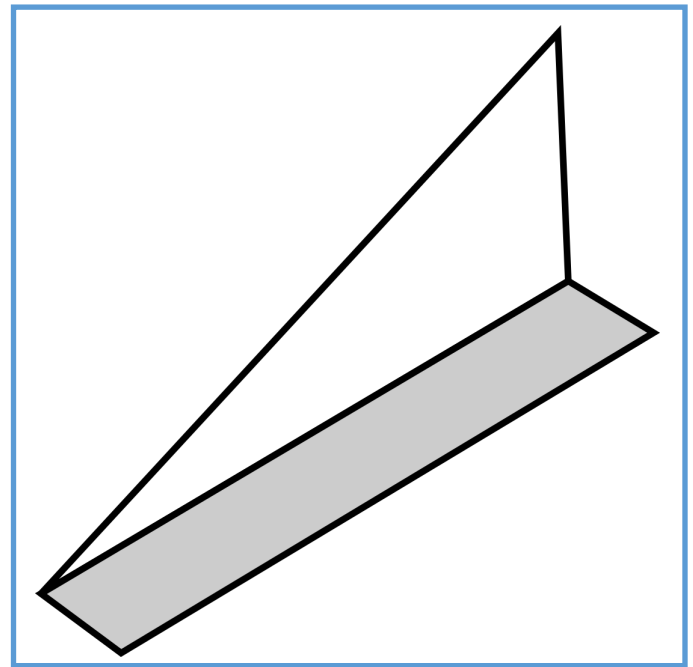
- [1] Chekab, M. A. (2013). Investigation of Different Methods of Noise Reduction for Submerged Marine Propellers and Their Classification. *American Journal of Mechanical Engineering, Vol. 1 (No. 2)*. Retrieved from: https://www.researchgate.net/publication/275515444_Investigation_of_Different_Methods_of_Noise_Reduction_for_Submerged_Marine_Propellers_and_Their_Classification
- [2] Renilson Marine Consulting Pty Ltd. (2009.). *REDUCING UNDERWATER NOISE POLLUTION FROM LARGE COMMERCIAL VESSELS[PDF]*. Retrieved from <http://ifaw-pantheon.s3.amazonaws.com/sites/default/files/legacy/Reducing%20Underwater%20Noise%20Pollutions%20for%20Large%20Commercial%20Vessels.pdf>



Vortex Generator

Overview:

Vortex generators are devices that help to smooth cavitation behavior and reduce vibrations. They are triangular appendages attached to both sides of the ship's hull near the aft shoulder. They work by producing a strong vortex that is carried into the propeller disc, which results in a smoother wake peak [1]. Computational model testing is required to optimize the specifications of the triangular shape, making them hard, but not impossible, to retrofit. There are no studies showing a reduction in underwater noise, but by improving cavitation behavior and reducing vibrations, it is assumed that noise will be reduced.



Cost

There are no estimates for purchase or installation costs. It is understood that to effectively implement vortex generators, computational model testing will need to be done.

Noise Reduction

Currently, there is no measured noise reduction. It has been shown that vortex generators could reduce propeller induced hull pressure pulses by 50% in the first four harmonics for both model and full scale tests [2].

Market Availability

Vortex generators are commercially available. They are frequently used in the airline industry, but the same principle has been tested on ships.

Efficiency Impact

A decrease in propulsive efficiency up to 2% was measured, but a reduction of pressure pulses by 50% was also achieved [1].

Implementation

Vortex generators can be retrofitted but because of the necessary computational model testing required, they should be considered for new builds only.

Additional Maintenance

Little to no additional maintenance is expected with the use of vortex generators. There are no moving parts and normal upkeep of the device is required.

References:

- [1] Johannsen, C. (2006). HSVVA Prediction confirmed: vortex generator fins reduced the vibration excitation level in full scale, HSVVA NewsWave, the Hamburg Ship Model Basin Newsletter, 2006/1.
- [2] Renilson Marine Consulting Pty Ltd. (2009.). *Reducing Underwater Noise Pollution From Large Commercial Vessels [PDF]*. Retrieved from: <http://ifaw-pantheon.s3.amazonaws.com/sites/default/files/legacy/Reducing%20Underwater%20Noise%20Pollutions%20for%20Large%20Commercial%20Vessels.pdf>

