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Analysis of Ship Efficiency versus Underwater Radiated Noise

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Analysis of Ship Efficiency versus Underwater Radiated Noise

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Executive Summary

This study was conducted by JASCO and DW-ShipConsult (DWSC) for Transport Canada to determine whether a vessel's underwater radiated noise (URN) level can be reduced without compromising efficiency. For this investigation, efficiency was quantified using the Energy Efficiency Design Index (EEDI). EEDI was introduced by the International Maritime Organization (IMO) as a tool to compel shipbuilders and owners to gradually improve the energy efficiency of the global fleet. Under the EEDI regime, more stringent efficiency requirements are in place starting in 2013, 2015, 2020, and 2025. URN is an underwater pollutant unlike any other in that it travels rapidly from its origin, but it ceases immediately when the source is removed—this is unlike chemical pollutants that spread slowly from their source and remain in the environment for decades after release. The most pervasive effect of URN from shipping on the environment is an increase in low-frequency sound levels that interferes with the ability of marine life to communicate and to use environmental queues for foraging and navigating.

The report provides a summary of previous work to quantify the dependence of URN on vessel designs and operation parameters. Speed through the water and actual draft are most correlated with URN, with faster vessels being louder overall and deep draft vessels being louder above 100 Hz. Design parameters were less correlated with URN than the speed and draft, and the significant parameters change with vessel class. Generally, longer vessels are louder; most other size parameters are collinear with length and therefore cannot be independently assessed. Starting in 2017 Transport Canada implemented a voluntary vessel slowdown program in Haro Strait and Boundary Pass. This program found that applying an 11-knot speed limit through sensitive areas reduces the average noise levels by 2 dB or more, and the short-term sound levels by up to 12 dB. Thus, slower, smaller, and more lightly loaded vessels are associated with lower URN. This is at odds with trends in the shipping industry that are favouring larger and deeper vessels.

To explore the relationship between EEDI and URN we examined two classes of vessels: Aframax tankers (228-256 m long) as well as 14000 TEU container ships (~360 m long). For each class, the EEDI and URN for vessels built before and after 2013 were considered. We also wanted to compare the EEDIs for vessels of the same class built to the 2020 standards; we obtained sufficient design information for the Aframax tanker class, but not for the 14000 TEU container ships. For the 14000 TEU vessels we compared the EEDI and URN for four vessels built to the 2013 standard instead. The URN data were obtained from measurements made using underwater listening stations (ULS) in the Salish Sea, off the West Coast of Canada. Assessing the EEDI required the participation of the vessel owners who provided information on the designs of their vessels as well as permission to work with the VFPA data. Vessels specifications have been anonymized as they are unimportant to the results of the study.

We performed the analysis of the EEDI and URN for three tankers and five container ships. URN measurements for each vessel were selected so that the drafts and speeds at which the measurements were taken were as closely matched as possible. All vessels studied had EEDIs below the 2013 thresholds, and the container ships had EEDIs below the 2020 thresholds as well. No clear relationship between URN and EEDI was found. The variability in URN between vessels even of the same design was on the order of 6 dB, despite having similar drafts and speeds during the measurements. Our previous measurements of URN have shown that differences of greater than 6 dB are common, even for repeat measurements of the same vessel.

A consideration of the EEDI formula to understand the trade-offs between EEDI and URN was performed. EEDI depends on the design speed and engine power, not how the vessels are operated in practice. Analysis showed that best way to lower EEDI is to reduce the engine size and the design speed. The allowed EEDI thresholds are different for each class of vessel, and the dependence of EEDI on speed is also class dependent due to the typical efficiencies of each hull-form. The EEDIs for the container ships studied were far below their allowed thresholds while tankers were generally close to their thresholds. This means container ships have more margin in their EEDI to accommodate changes to decrease URN that also decrease efficiency.

Reducing design speed is a choice available to vessels that are currently optimized for higher speeds such as container ships; however, tankers and bulkers that already travel at slower speeds have few options available to easily achieve a lower EEDI. Based on existing measurement results, reducing speed

also reduces URN per vessel; however, if more vessels are needed to deliver the same amount of goods in the same time, then the net effect on URN and total greenhouse gas emissions is unclear. Alternately, the industry could switch to larger vessels; however, those tend to have higher noise emissions.

Another method of reducing emissions is to change engines and fuel types. The analysis of two versions of a new proposed Aframax tanker suggests that switching to an LNG main engine results in a ~20% reduction in GHG emissions compared to diesel, which allows the tanker design to meet their EEDI targets. The effects on URN from changing engine (fuel) types are unknown.

Propeller cavitation is the main source of URN for most commercial vessels, and we provide an analysis of how cavitation is affected by propeller design. As a rule of thumb, propellers are optimized for propulsive efficiency rather than the highest possible cavitation inception speeds which would minimize cavitation noise. Instead, the acceptable level of cavitation is defined by vibrations inside the vessel as proscribed by the Classification Societies. Thus, the improvements in underwater noise we are seeing from slower vessels (e.g. Haro Strait) are due in part to vessels reducing their speeds without optimizing their propellers. Retrofitting the vessels with optimized propellers would likely increase URN – i.e. obtaining lower noise emissions results in higher GHG emissions compared to the optimal configuration for a given speed.

Effects of a smooth wake field are also reviewed. Wake equalizing devices are known to increase vessel efficiency; however, no measurement of URN before and after installation of a WED has been performed.

Affecting change in vessel designs must be done in the context of the ship building, financing, ownership, and chartering industries. The report presents estimates of the maximum efficiency improvements that can be obtained by good design and optimized operations of a vessel. Most efficiency improvements must be applied at design time. The primary efficiency improvements during operations are associated with running the vessel at its design depth and speed. Because the builders, owners, and financiers are generally separated from the long-term operational costs of running vessels, there is limited incentive to build more efficient vessels. This reality was one of the motivations behind the IMO developing and mandating the EEDI. Reductions in URN are even more difficult to bring to the attention of builders and owners, as there are almost no financial incentives for reducing noise. All three of the ship owners that provided data on their vessels in our study are exceptions to this rule. They own and charter their vessels and hence are interested in their efficiency; they are also invested in their communities and appreciate that the value of minimizing noise is not financial.

From this study we conclude that to date the primary result of EEDI is a reduction in the average vessel speed, i.e., slow steaming that reduces the greenhouse gas emissions of individual vessels. The net effect of this change on the total emissions is unclear and requires further investigation. Achieving improved EEDI will not improve URN, except in the context of reduced operational speed, which may not be substantial if the vessels employ optimized propellers. The net effects of reduced speed on total noise emissions is unclear if more or larger vessels are the solution. The results from the Haro Strait and Boundary Pass measurements indicate that reducing the speed of vessels optimized for higher speeds does reduce URN over large areas.

The knowledge gaps identified in this study that could be addressed through follow-on work are:

a. Conduct a basin scale modelling study to examine the trade-offs between more slow, large vessels and fewer, but smaller and faster vessels.
b. Conduct a similar study to this one where we examine the relationship between the energy efficient operational index (EEOI) and URN.
c. Look for an opportunity to quantify the URN of a vessel before and after fitting a WED. Ideally multiple measurements of the vessel would be made in both states to reduce the variability inherent in vessel source level measurements.
d. Look for an opportunity to quantify the URN of vessel(s) that have switched to slow steaming before and after fitting an optimized propeller. Ideally multiple measurements of the vessel would be made in both states to reduce the variability inherent in vessel source level measurements.
e. Conduct an analysis of the VFPA URN data set to determine if there is a difference in noise profiles for vessels with LNG propulsion compared to those using diesel.

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Abbreviations

AIS	Automatic Identification System
BAR	Blade Area Ratio
BMS	Becker Marine Systems
CFD	Computational Fluid Dynamic
CPA	closest point of approach
DFO	Fisheries and Oceans Canada
DWSC	DW-ShipConsult
DWT	dead weight tons
ECHO	Enhancing Cetacean Habitat and Observation
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Index
EVDI	Existing Vessel Design Index
GHG	Green House Gas
HSVA	Hamburg Ship Model Basin
IMO	International Maritime Organization
ISO	International Organization for Standardization
MSL	monopole source level
NGO	non-governmental organization
NIOSH	National Institute for Occupational Safety and Health
NMFS	National Marine Fisheries Service
P/D	pitch/diameter
PK	peak sound pressure level
PTS	permanent threshold shift
R&D	research and development
RNL	radiated noise level
Ro-Ro	Roll-on Roll-off
RPM	revolutions per minute
SEL	sound exposure level
SFC	specific fuel oil consumption
SPL	sound pressure level
SRKW	Southern Resident Killer Whale
TEU	twenty-foot equivalent unit (for shipping containers)
URN	Underwater Radiated Noise
VFPA	Vancouver Fraser Port Authority
WED	wake equalizing devices

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16. Abstract

This study was conducted by JASCO and DW-ShipConsult (DWSC) for Transport Canada to determine whether a vessel's underwater radiated noise (URN) level can be reduced without compromising efficiency. For this investigation, efficiency was quantified using the Energy Efficiency Design Index (EEDI). EEDI was introduced by the International Maritime Organization (IMO) as a tool to compel shipbuilders and owners to gradually improve the energy efficiency of the global fleet. This study reviewed previous work and found that operational parameters (draft, speed) have a greater effect on URN than design parameters (age, size). We then performed an analysis of EEDI vs URN for three tankers and five container ships of different ages and did not find a relationship between EEDI and URN for these test cases. A detailed study of the factors that affect the EEDI was performed, along with a review of how propeller cavitation is related to URN. From this study we conclude that the primary result of IMO implementing EEDI is a reduction in the average vessel speed, i.e., slow steaming that reduces the greenhouse gas emissions of individual vessels. Reduced speed is associated with reduced URN for vessels that slow down without changing their engines or propellers. The reductions in URN are likely to be reduced in the future if vessels are re-fit to employ propellers optimized for their new operational speed. Recommendations for future investigations are provided.

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16. Résumé

Cette étude a été effectuée par JASCO et DW-ShipConsult (DWSC) pour Transports Canada afin de déterminer si le niveau de bruit rayonné sous l'eau (BRSE) d'un navire peut être réduit sans compromettre son efficacité. Pour cette enquête, l'efficacité a été quantifiée en utilisant l'Indice nominal de rendement énergétique (INRE). L'INRE a été introduit par l'Organisation maritime internationale (OMI) comme un outil pour obliger les constructeurs et les propriétaires de navires à améliorer graduellement le rendement énergétique de la flotte mondiale. Cette étude a examiné les travaux précédents et a découvert que les paramètres opérationnels (tirant d'eau, vitesse) ont une plus grande incidence sur le BRSE que les paramètres de conception (âge, taille). Nous avons ensuite effectué une analyse de l'INRE versus le BRSE pour trois vraquiers et cinq porte-conteneurs de différents âges et nous n'avons pas trouvé de relation entre l'INRE et le BRSE pour ces cas types. Une étude détaillée des facteurs qui ont une incidence sur l'INRE a été effectuée, en plus d'un examen sur la façon dont la cavitation des hélices est reliée au BRSE. À la fin de cette étude, nous avons conclu que le principal résultat de la mise en œuvre par l'OMI de l'INRE est une réduction de la vitesse moyenne d'un navire, c.-à-d. la navigation à vitesse réduite qui réduit les émissions de gaz à effet de serre des navires individuels. La réduction de vitesse est associée à la réduction de BRSE pour les navires qui ralentissent sans changer leurs moteurs ou leurs hélices. Les réductions de BRSE diminueront probablement à l'avenir si les navires sont remis en état pour utiliser des hélices optimisées pour leur nouvelle vitesse opérationnelle. Des recommandations pour des enquêtes futures sont fournies.

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1. Introduction

Enhancing a vessel's efficiency reduces its carbon footprint and its operating costs at the same time. Because of this, most research and development (R&D) activities related to vessel designs have focussed on efficiency improvements. As Underwater Radiated Noise (URN) is becoming a new environmental footprint of concern, the effects of vessel design alterations on efficiency and URN need to be investigated more closely. A recent study of correlations of URN with vessel design and operating characteristics (MacGillivray et al. 2020) found that vessel speed through the water, length, and draft were most strongly correlated with URN—vessels that were faster and larger generate more URN. Other factors, including main engine power, engine revolutions per minute (RPM), auxiliary engine power, and design speed had a secondary (though still statistically significant) influence on URN.

It is known that the dominant source of URN for most commercial vessel traffic is cavitation from the propeller. We know that an acoustically optimized propeller leads to decreased energy efficiency and conversely, the most efficient propellers show significant potential for acoustic improvement. Thus, achieving optimized efficiency and URN is not straight-forward. Aside from these technical aspects, the commercial implications and the decision-making processes surrounding the design and operation affect the choices made to improve vessels. It is essential to understand these processes and the interests of all stakeholders to find the correct way to approach the issue of vessel efficiency and URN.

The regulatory setting needs to be considered as well. With the introduction of the Energy Efficiency Design Index (EEDI) regulation in 2013 by the International Maritime Organization (IMO) and the approaching stricter rules, vessel design, building, and operation processes will face new challenges and restrictions. These regulations will influence future vessel efficiency and URN emissions.

This study was conducted by JASCO and DW-ShipConsult (DWSC) for Transport Canada to determine whether a vessel's URN level can be reduced without compromising efficiency. It describes the shipbuilding parameters that influence efficiency and URN. In this regard, the focus is on propellers and wake fields. This report also describes the EEDI regulation and calculation process, its likely effect on the shipping industry, and how it is expected to improve vessel efficiency and URN emissions. With a description of the typical vessel design and purchase process, we shed light on the interests of the different stakeholders and point out that improvements can only be achieved if the party who decides to invest in improvements is also the party who benefits from them in the end.

The study focused on commercial vessels, as they are the most common vessels in the oceans. The two vessels classes expected to visit the Vancouver Fraser Port in greater numbers in the future were investigated in more detail:

a. The Aframax tanker vessel class.

b. Container ships between 13,000 and 15,000 twenty-foot equivalent units (TEU).

For each of the two vessel classes, three individual vessels were investigated:

a. A vessel built before 2013 (without specific design considerations for EEDI compliance).

b. A vessel built shortly after 2013 under Stage One EEDI considerations.

For the Aframax tanker, a hypothetical vessel designed and built under a later stage of EEDI considerations (efficiency optimized at best). For the 14000 TEU container vessel, multiple measurements of the same class of post-2013 vessels were compared to evaluate variability in URN at the same EEDI.

For these vessels, the EEDI was calculated and the respective URN was analyzed based on measurements contained in a database maintained by the Enhancing Cetacean Habitat and Observation (ECHO) program of the Vancouver Fraser Port Authority (VFPA). These examples explore the potential for acoustic improvement at a given efficiency. Uncertainties and areas for further investigation are documented, and a research program to advance our understanding of efficiency and underwater radiated noise is recommended.

1.1. Using EEDI to Improve Environmental Footprints

Although conserving fuel and reducing the resulting CO_2 emissions should be a major intrinsic motivation for every stakeholder in the shipping industry, the economics of vessel construction work against efficiency improvements. Partially in response to this, the IMO developed a mandatory regulation with the aim to reduce CO_2 emissions of the shipping industry: EEDI, which is introduced here and discussed further in Section 3.

EEDI went into effect in 2013 with subsequent phases planned for 2020 and 2025 (IMO 2018). It aims to minimize CO_2 consumption as measured at the maximum transport capacity for new vessels. The IMO estimates that introducing EEDI will reduce CO_2 emissions by 45 to 50 million tons per year in Phase One and up to 180 and 240 million tonnes per year from 2030 onwards (IMO 2018). Improved designs of the propulsion systems and hull design as well as larger vessel sizes and smaller engines (i.e., lower operating speeds) are the main parameters that are reducing CO_2 emissions. The IMO's intention was for EEDI to stimulate research in a holistically efficient vessel and propulsion design at the building stage, leading to more energy-efficient vessels with reduced CO_2 emissions. The regulation only considers new vessels, which means that EEDI improves the environmental footprint regarding CO_2 emissions for new vessels built from 2013 onward.

The operational usage of vessels is not covered by the EEDI regulations, but technical guidelines that reduce CO_2 emissions during operations, such as lower speed and voyage optimization, can be found in the voluntary Energy Efficiency Operational Index (EEOI) applicable for all vessels (MEPC.1/Circ.684; IMO 2009).

1.2. Underwater Noise and Effects on Marine Life

Sound propagates much farther underwater than light or scent, which has led marine life to use hearing as a primary means for sensing their environment. All fish examined have at least a rudimentary hearing capability. Many use sound for navigating, selecting habitat and mates, and avoiding predators (Popper and Hawkins 2019). Many invertebrates also have means of sensing sound, and they react to sudden sounds (Edmonds et al. 2016). Marine mammals make extensive use of sound for foraging, navigating, avoiding predators, mating, and rearing young (Richardson et al. 1995).

Sounds in the ocean have three primary sources (Figure 1):

a. Natural sounds from wind, waves, ice, and seismic (tectonic) activity.

b. Biologic sounds from fish, invertebrates, and marine mammals; and

c. Human sound sources.

Figure 1 indicates the approximate frequency bands occupied by these sources, as well as their relative level, both at the sound source and for the ambient soundscape. For the present study, the primary man-made source of sound of interest is shipping.

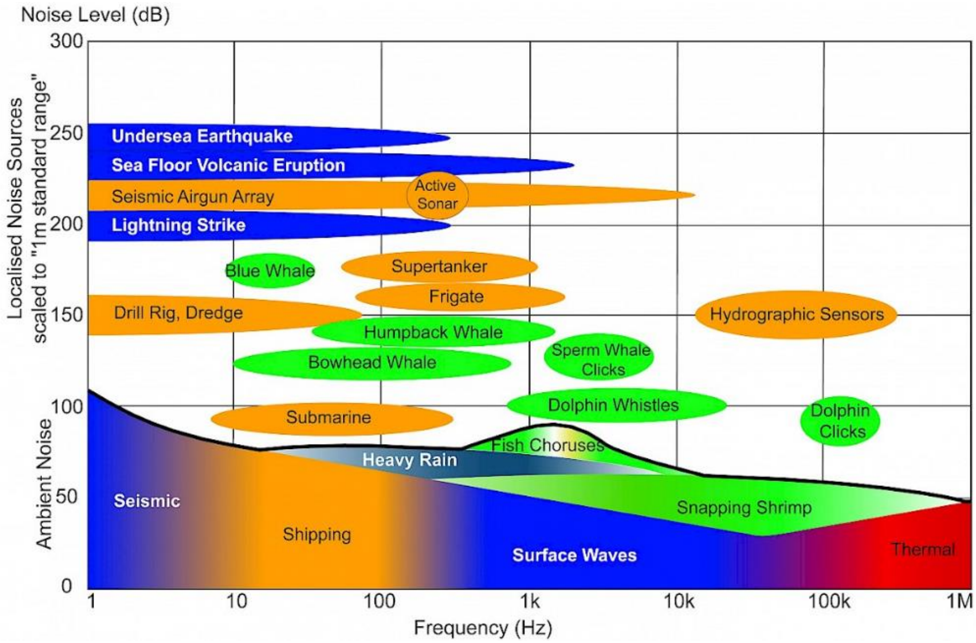


Figure 1. Sounds in the ocean. The spectral level of typical sound source, when measured at 1 m from the source, and the typical ambient noise levels measured by a recorder. Yellow sources are man-made, blue are natural geologic, and green are biologic. Thermal noise is the limit of what can be measured at high frequencies due to electronic self-noise. Image from OSPAR Commission (2020).

The effects of human sounds on marine life are well documented and often described using a zone model (Figure 2). In Zone 1, lethal effects of barotrauma (Halvorsen et al. 2012, Dahl et al. 2020) and permanent hearing injury occur (Southall et al. 2019). In Zone 2, there is temporary injury to hearing, which can have short term effects on an animal's abilities and survival. In Zone 3, masking of biologically important sounds (Erbe et al. 2015) occurs. In Zone 4, the sounds are audible and may continue to have behavioural or physiological stress effects on the animals (Rolland et al. 2012, Shannon et al. 2016). Reducing underwater sound levels has been identified as an important thrust of endangered species recovery plans within Canada (DFO 2011, 2014) and as part of international advances in environmental stewardship (IMO 2014a, Dekeling et al. 2014, Gedamke et al. 2016).

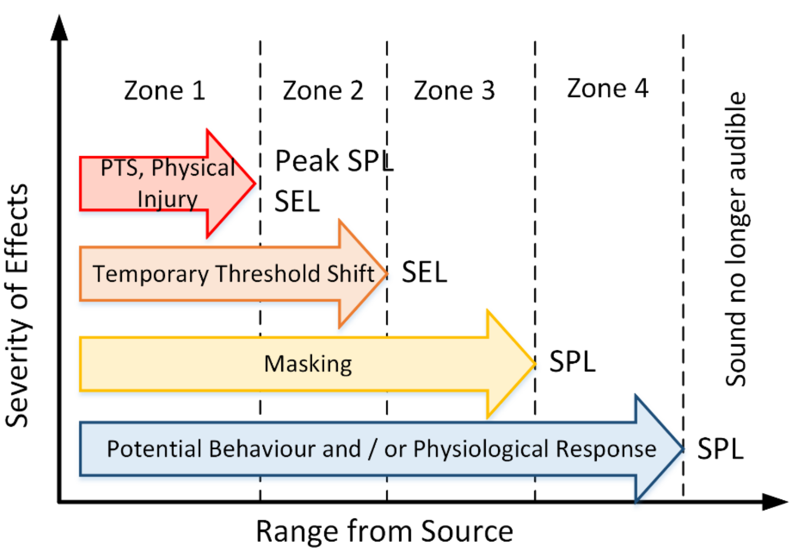


Figure 2. General principles of sound exposure as four zones. PTS is permanent hearing threshold shift. SPL is sound pressure level, SEL is sound exposure level. Image based on Dooling et al. (2015).

The acoustic measurement that is associated with the different types of hearing injury are also shown in Figure 2. Peak sound pressure level (PK), sound pressure level (SPL), and sound exposure level (SEL) are linked to physical injury and hearing threshold shifts. The sound from vessels never has PK levels high enough to be of concern. The SPL is associated with masking and behavioural responses. SPL in decibels (dB) is 10 times the logarithm (base 10) of the sound pressure, which is the integral of the squared sound pressure over some period of time, *T*, normalized by a reference squared pressure P_o^2 and integration time *T* (see also ISO (2017)):

$$L_{P,\mathrm{W,T}} = 10\log_{10}\left(\frac{1}{T P_o^2}\int_0^T p_w^2(t)\,dt\right)\mathrm{dB}\,, \tag{1}$$

where P_o is 1 µPa, so that $L_{P,\mathrm{W,T}}$ is in dB with a reference of 1 µPa². SEL in dB is 10 times the logarithm (base 10) of the sound exposure, which is the integral of the squared sound pressure over some period of time, *T*, normalized by a reference squared pressure P_o^2 and reference time T_o (see also ISO (2017)):

$$L_{E,\mathrm{W,T}} = 10\log_{10}\left(\frac{1}{T_0 P_o^2}\int_0^T p_w^2(t)\,dt\right)\mathrm{dB}\,, \tag{2}$$

where T_o is normally 1 s and P_o is 1 µPa, so that $L_{E,\mathrm{W,T}}$ is in dB with a reference of 1 µPa²·s. The 'W' in these equations represents the auditory frequency weighted pressure that accounts for the hearing capability of an animal (see paragraph below). The primary difference between SEL and SPL is that SEL integrates over the time of exposure (or 24 h, whichever is shorter), whereas SPL is the average value or a representative period of time (e.g., 1 s or 1 min for a continuous source, such as a vessel).

When determining potential effects of a sound source, the pressure should be scaled according to an animal's sensitivity to different frequencies. For human hearing, we use the 'A-weighting' auditory weighting function to filter sounds before estimating the effects (NIOSH 1998). The weighting function is an inversion of an audiogram (or equal-loudness curves when they exist), normalized to have a gain of zero at the frequencies of peak sensitivity. For marine mammal hearing, species are separated into hearing groups, each with its own auditory weighting function (Figure 3). These weighting functions, first developed by Finneran (2016), are based on detailed analysis of existing audiogram data and other inputs and have been incorporated into the Technical Guidance issued by American regulators for assessing effects of human-generate underwater noise on marine mammals (NMFS 2018, Southall et al. 2019). No such generalized weighting functions exist for fish or invertebrates.

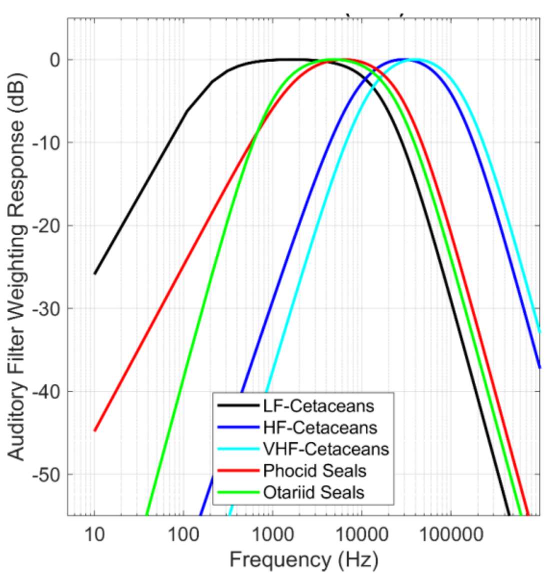


Figure 3. Auditory weighting functions for the marine mammal hearing group (Southall et al. 2019). Low-frequency cetaceans include the large baleen whales (e.g., blue, fin, humpback whales). High-frequency cetaceans are the dolphins, sperm whales, and beaked whales that whistle and echolocate in the ~1000–80,000 Hz band. Very-high-frequency cetaceans are the dolphins, dwarf sperm whales, and porpoises that echolocate at ~130 kHz. Otariid seals are sea lions and fur seals. Phocid seals are considered 'true' seals.

2. Summary of Current Knowledge of Dependence of URN on Vessel Design and Operational Parameters

2.1. Correlation of URN with Operational and Design Parameters

Many past studies have demonstrated that vessel URN is strongly correlated with vessel speed and size (Ross and Alvarez 1964, Arveson and Vendittis 2000, McKenna et al. 2013, MacGillivray et al. 2019) and that vessel class (and hence design) is also a strong determiner of URN (Bassett et al. 2012, McKenna et al. 2012, Veirs et al. 2016). However, the reported influence of these factors has not necessarily been consistent between past studies (Chion et al. 2019), which may be attributed (in part) to differences in measurement methodologies and limitations of historical data sets. To address historical data gaps and shortcomings with past studies, the VFPA ECHO program, in partnership with JASCO and Transport Canada, has been collecting thousands of systematic source level measurements for vessels of opportunity in the Salish Sea since 2015. Furthermore, the protocol for these measurements is guided by the ANSI S12.64 standard, in order to ensure repeatable, consistent results (Hannay et al. 2016).

A recent study by the VFPA ECHO program examined statistical correlations between vessel URN and design and operational parameters, using source level measurements collected by ECHO during 2015–2018 (MacGillivray et al. 2020). The ECHO study found that speed through water and actual draft (i.e., the two primary operational parameters) were the most influential factors determining vessel URN for all vessel categories examined. Higher speed through water was correlated with higher URN in all frequency bands, and deeper vessel draft was correlated with higher URN above 100 Hz. Thus, the ECHO study found that slower steaming and lighter loading conditions are generally associated with lower vessel URN.

The ECHO study also found that vessel design parameters (as furnished by Lloyds List Intelligence) were more weakly correlated with URN than operational parameters. Furthermore, the observed trends were often different between vessel categories. Vessel size (as measured by length overall) was the design characteristic that generally had the strongest correlation with URN, and larger vessels tended to have higher overall URN. Other size-related parameters, such as beam, displacement, and gross tonnage were strongly correlated with length and so their influence on URN could not be separated from length (or from one another). Four other design parameters were found to have a weaker, but statistically significant, influence on URN: main engine power, auxiliary engine power, main engine RPM, and design speed. The relative influence of these four design parameters varied between vessel categories, however. Other design parameters were either found not to have a statistically significant influence on URN (e.g., block coefficient, summer draft) or were data deficient (e.g., number of main engines, number of propellers). Note, however, that the design parameters examined by the ECHO study were not exhaustive, and many factors that may be expected to influence URN (e.g., propeller diameter, type of engine mountings, hull shape) were unavailable.

2.2. Correlation of URN with GHG Emissions

The ECHO study (MacGillivray et al. 2020) also examined statistical trends between URN and greenhouse gas (GHG) emissions, across decade frequency bands, for two broad categories of vessels (Figure 4). While the observed correlations were relatively weak (i.e., the scatter of the URN data exceeded the range of the estimated trends), the following trends were observed:

a. For fast cargo vessels (container ships and vehicle carriers), lower intensity of GHG emissions were correlated with higher URN across all frequency bands.

b. For slow cargo vessels (bulker carriers and tankers), lower intensity of GHG emissions were correlated with higher URN below 100 Hz and with lower URN above 100 Hz.

Thus, the ECHO study found that lower intensity of GHG emissions were often associated with higher URN, though the observed trends were weak and varied with vessel type.

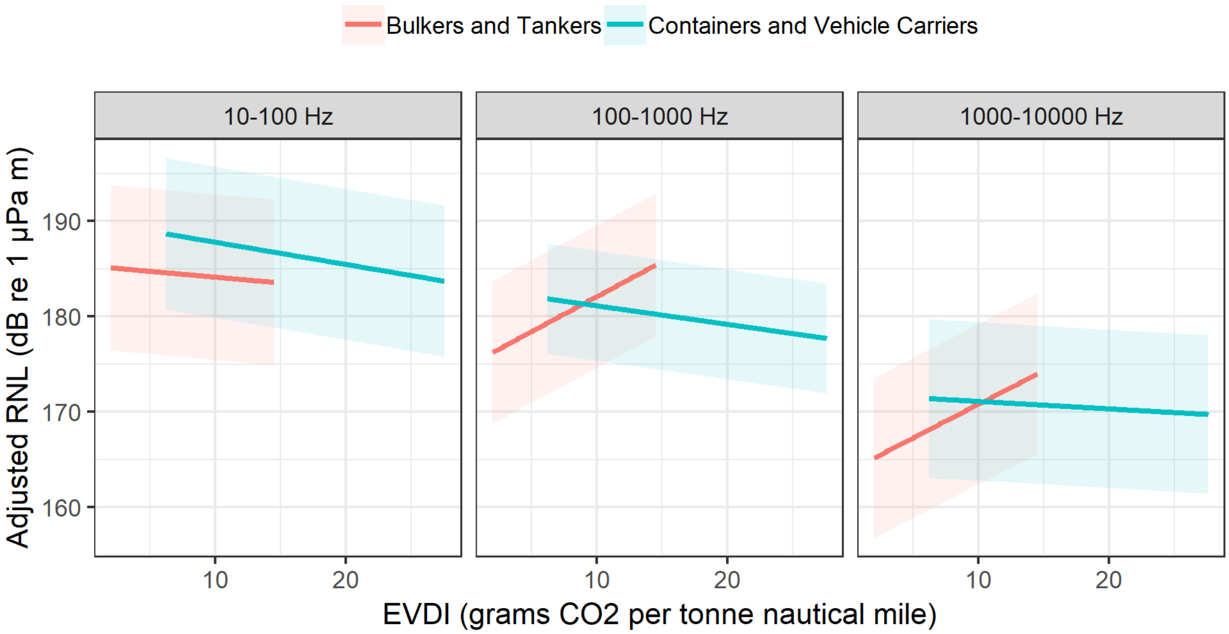


Figure 4. Estimated trend of adjusted radiated noise level (RNL), in decade frequency bands, versus Existing Vessel Design Index (EVDI) from the ECHO vessel noise correlations study (MacGillivray et al. 2020). Adjusted RNL values are obtained by scaling measured RNL values according to mean speed through water and vessel draft conditions (by category). The solid lines represent the best-fit linear trends over the 99% EVDI range. The shaded areas represent the 95% prediction intervals for RNL. The wide prediction intervals reflect the fact that the observed trends explain a relatively small fraction of the total data variance ($0.002 \leq r^2 \leq 0.156$).

The ECHO study used the Existing Vessel Design Index (EVDI), rather than EEDI, for measuring GHG emissions, as most vessels in the ECHO data set were built before 2013 and do not have EEDI ratings. The EVDI is a theoretical measure of CO_2 emissions, like EEDI, that is calculated from ship design and engine performance data. According to RightShip (who developed the EVDI rating), EVDI and EEDI are largely compatible:

> "[EVDI] measures a ship's theoretical CO_2 emissions per nautical mile travelled. However, the EVDI can be applied to existing vessels as well as new builds (where EEDI is not available/ applicable). As the two methods compare relative efficiency on the same basis, a like-for-like comparison of efficiency is achievable." (RightShip 2020)

Note that the statistical analysis controlled for speed-related changes in URN, and thus the trends in Figure 4 do not account for additional reductions in noise and GHG emissions that may be achieved by slow steaming. Leaper (2019) estimated that speed reductions associated with slow steaming could further reduce sound energy from global shipping while also reducing overall GHG emissions.

2.3. Salish Sea Slow-down Studies

In 2017, Transport Canada commissioned a desktop modelling study to assess underwater shipping noise levels in the Salish Sea and to investigate the effectiveness of several possible noise mitigation approaches after an increase in commercial traffic in the area (Matthews et al. 2018). In that study, baseline noise levels were established by modelling vessel traffic densities based on 2015 Automatic Identification System (AIS) data. Future case scenarios represented predicted conditions for 2020. In these scenarios, the number of oil tankers transiting the area each month increased from 5 to 34, and 29 tugs were added (to escort the new tankers). The mitigation options included implementing a vessel slow-down zone in Haro Strait.

Limiting all commercial vessel speeds in SRKW critical habitat in Haro Strait to 11 kn led to slightly decreased vessel noise levels inside the slow-down zone. Broadband noise levels and Southern Resident Killer Whale (SRKW) audiogram-weighted average monthly sound pressure levels were studied. At the sampled locations near to shipping lanes, an 11 kn speed limit reduced broadband noise levels by 2.4 to 2.5 dB and SRKW-weighted noise levels by 1.3 to 1.9 dB. Farther away from the shipping lane, broadband noise levels were reduced by 0 to 2.0 dB and SRKW-weighted noise levels by 0 to 0.2 dB. In the speed transition zone (where vessels slowed down and sped up), a slight increase in SRKW-weighted noise level (+0.4 dB) was predicted. The Transport Canada modelling study concluded that a speed limit of 7 kn would produce approximately twice the reduction as the 11 kn speed limit.

In summer of 2017, the VFPA ECHO program conducted their first voluntary vessel slowdown trial in Haro Strait. From August 7 to October 6, vessels were requested to voluntarily slow their speed through water to 11 knots inside a 16 nm corridor in SRKW critical habitat. During the two-month trial, 61% of piloted vessels were reported as voluntarily participating, with 44% of vessels verified as having a transit speed less than 12 knots inside the slowdown corridor (ECHO 2018). Hydrophone measurements obtained 2.3 km from the shipping corridor showed that median SPLs (10-100,000 Hz) were reduced by 1.2 dB during the trial, when compared to baseline conditions, and that the reduction was 2.5 dB when filtered for time periods when commercial vessels were within 6 km of the hydrophone (Joy et al. 2019). Furthermore, reducing vessel speeds was found to reduce their mean underwater radiated noise by 5.9–11.5 dB (MacGillivray et al. 2019).

Following the success of the 2017 trial, the ECHO program has continued to implement voluntary slowdowns during summer in Haro Strait and, starting in 2019, Boundary Pass. ECHO adjusted the voluntary speed limits in subsequent years, with the goal of increasing overall participation. During the 2019 slowdown period, for example, slower vessels (Tankers, Bulk Carriers, and General Cargo vessels) were requested to slow to 11.5 knots whereas faster vessels (Containerships, Vehicle Carriers, and Cruise vessels) were requested to slow to 14.5 knots. Reported participation was 87% in 2019, with 67% of vessels verified to be travelling within 1 knot of the requested speed limit. Hydrophone measurements during 2019 showed that median sound levels were reduced by 3.0 dB in Haro Strait and 3.5 dB in Boundary Pass, when compared to baseline periods (ECHO 2020). In August 2019, VPFA signed a 5-year conservation agreement with the Government of Canada that will see voluntary slowdowns continue in SRKW critical habitat through at least 2023 (DFO 2019).

3. The Energy Efficiency Design Index

3.1. Overview of the EEDI

A key question of this study is: Does EEDI relate to vessel efficiency? EEDI is an indicator of potential *transport* efficiency and not *vessel* efficiency. This has many aspects, not only technical ones. Currently, we only consider the influence of achieving a certain EEDI value on the quality of the vessel.

The core of the EEDI equation is:

$$\text{EEDI} = \frac{C_{F,ME} \cdot \text{SFC}_{ME} \cdot f_j \cdot P_{ME} + C_{F,AE} \cdot \text{SFC}_{AE} \cdot P_{AE}}{f_i \cdot \text{capacity} \cdot v} = \frac{C_F \cdot (\text{SFC}_{ME} \cdot f_j \cdot P_{ME} + \text{SFC}_{AE} \cdot P_{AE})}{f_i \cdot \text{capacity} \cdot v}, \quad (3)$$

where

- P_{ME} is rated power of the main engine; if the engines, hull, wake field, or propeller are improved so that less power is required to achieve the same speed, the decreased power is the term where efficiency improvements will show up.
- P_{AE}: Auxiliary Engine Power
- C_F expresses the amount of CO_2 emitted per ton of fuel burnt,
- SFC is specific fuel oil consumption,
- v is maximum speed achieved with the rated power.
- Capacity depends on the vessel type. For tankers it is DWT (deadweight tonnage), for container vessels it is 0.7*DWT.
- f_i and f_j are correction factors applicable for different vessel classes. For the tanker, these factors are defined as “1”. For the considered container vessels, the calculation showed a number >1, which automatically sets the value to “1”.

Equation 3 shows the attained EEDI for a singular vessel design. This value is then compared with the required EEDI computed for the vessel class. Figure 5 shows the original reference EEDI for tankers and container vessels. For vessels built after 2025, these values will be lower by 30%.

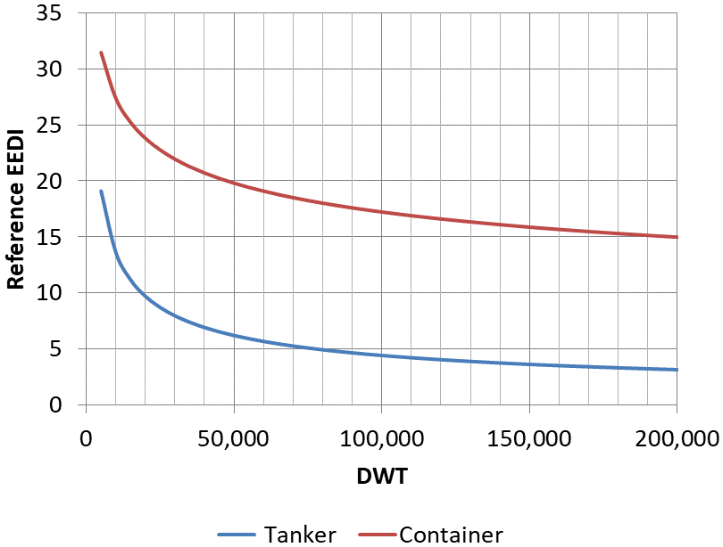


Figure 5. 2013 Reference Energy Efficiency Design Index (EEDI, on y-axis) for tankers and container vessels versus the vessel capacity (DWT = dead weight tons) (Equation 4) for X = 0).

The required EEDI, as defined in IMO Resolution MEPC.203(62), is calculated with the following equation:

$$EEDI_{required} = \left(1 - \frac{X}{100}\right) \cdot a \cdot b^{-c} \tag{4}$$

The factors a, b, and c are related to the type of vessel derived from regression of existing vessels and set the limits on the efficiency that must be achieved. The factor X depends on the phase (2013, 2015, 2020, and 2025). The factor X is zero for phase 0 (2013) and, at most, increases for every next phase by 10.

Table 1. Required Energy Efficiency Design Index (EEDI) parameter table from IMO Resolution MEPC.203(62) from 15Jul 2011 (Table 2 in IMO 2014b).

Ship type defined in regulation 2	a	b	c
2.25 Bulk carrier	961.79	DWT of the ship	0.477
2.26 Gas carrier	1120.00	DWT of the ship	0.456
2.27 Tanker	1218.80	DWT of the ship	0.488
2.28 Container ship	174.22	DWT of the ship	0.201
2.29 General cargo ship	107.48	DWT of the ship	0.216
2.30 Refrigerated cargo carrier	227.01	DWT of the ship	0.244
2.31 Combination carrier	1219.00	DWT of the ship	0.488
2,33 Ro-ro cargo ship (vehicle carrier)	$(DWT/GT)^{-0,7}$*780.36 where DWT/GT < 0,3; 1812.63 where DWT/GT ≥ 0.3	DWT of the ship	0.498
2.34 Ro-ro cargo ship	1405.15	DWT of the ship	0.498
2.3.5 Ro-ro passenger ship	752.16	DWT of the ship	0.381
2.38 LNG carrier	2253.7	DWT of the ship	0.474
2,39 Cruise passenger ship having non-conventional propulsion	170.84	GT of the ship	0.214

In addition, there are several other factors that influence EEDI, such as the effect of a power take-off (generator driven by the main engine) and other effects of lesser influence that do not hinder comparing different vessels of the same type.

In the following discussion, we assume C_F and SFC are constant and unaffected by efficiency considerations.

Combining Equations 3 and 4 we get Equation 5 with the core of the EEDI formula:

$$\mathrm{EEDI} = \frac{P_{ME} \cdot c_{F,ME} \cdot \mathrm{SFC}}{\mathrm{v} \cdot \mathrm{DWT}} \leq \mathrm{a} \cdot \mathrm{DWT}^{-\mathrm{c}} \tag{5}$$

When considering Equation 5, some peculiarities become apparent.

Rated power, P, is in the numerator, and speed, v, is in the denominator. However, the relationship between P and v is that $\mathrm{P} \sim v^3$ for slow vessels, such as tankers and bulk carriers. For fast vessels, the exponent can be as high as 4 or 5. The reason for this is that slow vessels are dominated by viscous resistance effects, while fast ones suffer from increasing wave-making resistance that rises faster with speed than friction resistance

The left-hand side of Equation 5 represents a simplified expression of the formula for attained EEDI. For a given vessel, we may assume that the factors $C_{F,ME}$, SFC and DWT are constant, thereby simplifying the expression further, so we see that Attained EEDI is proportional to P_{ME}/v. For a given vessel speed, attained EEDI may be reduced (improved) by improving the vessel efficiency and therefore, reducing the power required to reach that speed. As discussed in Section 6, it is technically feasible to improve vessel efficiency by 5% and with more effort to achieve 10 to 20% efficiency improvement. However, an EEDI improvement of the same scale can also be achieved if the operating speed is reduced and engine power (P_{ME} in the EEDI formula) is reduced accordingly; in other words, no actual improvement is made to the vessel's efficiency. Equation 6 shows the calculation of the reduced speed that would be necessary for a tanker with initial operating speed of 15 kts to improve/reduce the Attained EEDI by 5%, recalling that attained EEDI is proportional to P/v and P is proportional to v^3:

$$v_{new} = \frac{1}{\sqrt[2]{1.05}} \cdot 15 = 14.64 \text{ kts} . \tag{6}$$

In other words, for the example tanker, substantial design effort could be made to improve efficiency by 5%, while a speed reduction down to 14.64 knots would have the same effect. For a 20% improvement, the necessary speed reduction would be to 13.7 knots from 15 knots.

The simplest way for the ship owner/shipyard team to meet EEDI is to use the old vessel (cheap, no additional design cost) and remove a cylinder from the main engine (for example) so it can only travel at 14 kts, rather than 15 kts as before. For vessel operators, this carries the advantage of decreasing fuel costs but the disadvantage of increasing other operating costs (e.g., crew and capital cost for more vessels needed to move the same amount of cargo in the same amount of time).

In total, this means that EEDI improvements for some vessel types may be very easy to achieve without any extra optimization. This bears the risk that EEDI will not lead to any efficiency improvements of vessel designs but only to reduced operating speeds. The Haro Strait vessel slowdown study (MacGillivray et al. 2019) demonstrated that speed reductions also decrease underwater radiated noise (see Section 2).

If we accept the fact that EEDI is most likely achieved with low design speeds, we need to consider the following disadvantages of this with respect underwater radiated noise:

- A slower journey leads to a longer time passing a point in the ocean—this may lead to an increased sound exposure level, even if the sound pressure level is reduced.
- The market demand for a timely provision of a certain amount of goods at a certain location will find alternative transport paths, (i.e., rail, road, or aircraft) that are connected to substantially higher carbon emissions per mile and cargo ton.

- More vessels will have to transit on the same route, leading to higher carbon and underwater noise emissions.
- Bigger vessels with more cargo capacity and an increased demand for harbour infrastructure will be needed.
- The current market situation for transport vessels is still dominated by overcapacity. As soon as the market situation changes, the above-mentioned evasion effects will immediately be implemented, leading to a substantial increase in carbon emissions and URN.

Summarized, the following can be said:

- EEDI is a program supporting slow steaming (lower design speed of vessels).
- EEDI does not necessarily lead to any efficiency improvements of the vessel design.
- EEDI will lead to vessels with lower rated powers.
- Slower speeds generally reduce URN; however, efficiency improvements without reducing speed may also reduce URN.

3.2. EEDI Calculation and Comparison for the Vessels Analyzed

Table 2 shows the vessels that have been considered for EEDI and URN analysis. The EEDI was calculated on the basis of Equations 3 and 5). The EEDI required in 2013 is listed in the far-right column. Actual EEDIs need to be below the required EEDI. Due to confidentiality reasons, all vessel names are anonymized. The build category and the EEDI values are correct. All other numbers and values of technical data is rounded in different magnitudes and different directions to prevent an identification.

Table 2. Energy Efficiency Design Index (EEDI) calculated for the vessels considered in this analysis.

Category	Vessel name	Size (DWT)	EEDI	Req. 2013
Pre-2013 Aframax	Afra 1	106,800	3.69	4.27
Post-2013 Aframax	Afra 2	102,000	3.32	4.32
Modern Aframax	Afra 3	87,900	2.86	4.69
Pre-2013	Con 1	150,000	9.19	15.97
Post-2013	Con 2a	140,000	9.19	16.05
Post-2013	Con 2b	140,000	9.19	16.05
Post-2013	Con 2c	140,000	9.19	16.05
Post-2013	Con 2d	140,000	9.19	16.05

Sister vessels of the post-2013 Container Class all feature the same EEDI. In all cases, the EEDI is well below required limits. This is also valid for those vessels built before 2013 although the margin is lower.

EEDI was calculated with the help of input data from the ship owners and assumptions made to complete the required information. Tables 3 and 4 provide an overview on all input data, the resulting EEDI and the four EEDI requirements (2013, 2015, 2020, and 2025). As in Table 2, specific values for the vessels have been rounded for anonymity.

Table 3. Values employed for calculating the Energy Efficiency Design Index (EEDI) for the Aframax class vessels.

Vessel feature	Afra 1	Afra 2	Afra 3 Gas	Afra 3 Oil
MCR [kW]	13000	12000	10000	10000
DWT [t]	106800	102000	88000	88000
Speed [kn]	14	16	14	14
P_ME [kW]	10000	9000	7500	7500
P_AE at normal seagoing condition [kW]	570	560	510	510
Specific fuel consumption ME [g/kWh]	160	170	140	180
Specific fuel consumption AE [g/kWh]	200	200	150	190
cF (HFO) [tCO2/tFuel]	3	3	3	3
cF (LNGl) [tCO2/tFuel]	2.8	2.8	2.8	2.9
cF (Diesel) [tCO2/tFuel]	3.15	3.15	3.15	3.15
f_i	1	1	1	1
f_j	1	1	1	1
Year Built Category	Pre-2013	Post-2013	not built	not built
EEDI_attained [gCo2/tnm]	**3.69**	**3.32**	**2.86**	**3.97**
a	1218	1218	1218	1218
b	106800	102000	88000	88000
c	0.488	0.488	0.488	0.488
EEDI_required 2013	4.26	4.32	4.69	4.69
EEDI_required 2015	3.84	3.89	4.21	4.21
EEDI_required 2020	3.42	3.46	3.75	3.75
EEDI_required 2025	2.99	3.02	3.28	3.28

There appears to be a trend where vessels built more recently have lower EEDIs (Table 3). The Afra 2, built in 2013, has an EEDI which would not be allowed for a newbuild after 2025. The Afra 3 design is not built yet.

There are several designs and fuels considered for the post-2020 Aframax tanker. In our calculation we took one design with two different fuel options. We can see that the new design with the conventional fuel oil will not meet the 2020 EEDI criteria. If the gas design is selected, a compliance of a newbuild with the EEDI requirement can be expected beyond 2025. These values show that a compliance with the criteria is challenging for this vessel class.

Table 4. Values employed for calculating the Energy Efficiency Design Index (EEDI) for the 14000 TEU containership class vessels.

Vessel feature	Con 1	Con 2a	Con 2b	Con 2c	Con 2d
MCR [kW]	72000	45333	45333	45333	45333
DWT [t]	150000	140000	140000	140000	140000
Speed [kn]	25	20	20	20	20
P_ME [kW]	54000	34000	34000	34000	34000
P_AE at normal seagoing condition [kW]	2000	1400	1400	1400	1400
P_PTI (75% of installed) [kW]	0	0	0	0	0
P_PTO (75% of installed) [kW]	0	0	0	0	0
Specific fuel consumption ME [g/kWh]	170	170	170	170	170
Specific fuel consumption AE [g/kWh]	200	200	200	200	200
cF (HFO) [tCO2/tFuel]	3	3	3	3	3
cF (LNGl) [tCO2/tFuel]	2.8	2.8	2.8	2.8	2.8
cF (Diesel) [tCO2/tFuel]	3.15	3.15	3.15	3.15	3.15
f_i	1	1	1	1	1
f_j	0.7	1	1	1	1
Year Built Category	Pre-2013	Post-2013	Post-2013	Post-2013	Post-2013
EEDI_attained [gCo2/tnm]	9.2	9.19	9.19	9.19	9.19
a	174.22	174.22	174.22	174.22	174.22
b	150000	140000	140000	140000	140000
c	0.201	0.201	0.201	0.201	0.201
EEDI_required 2013	15.97	16.05	16.05	16.05	16.05
EEDI_required 2015	14.37	14.45	14.45	14.45	14.45
EEDI_required 2020	12.78	12.84	12.84	12.84	12.84
EEDI_required 2025	11.18	11.23	11.23	11.23	11.23

The attained EEDI of the analyzed container vessels all comply with current and future EEDI requirements (Table 4). The margin is considerably larger compared to the Aframax vessels. Although the available data set is not representative for the worldwide tanker and container fleet, it gives a rough impression of the situation. In addition to these vessels, we calculated the EEDI for five additional vessels. These include considerably smaller (1/3rd or 1/6th of Con 2 DWT) and older (1999 to 2003) container vessels. These smaller and older vessels have EEDIs that comply with the 2025 EEDI requirement. Only one vessel with a very high installed power was above the limits.

This leads to the hypothesis that the dominant influence on the margin b between attained EEDI and required EEDI is the vessel type specific reference constant "c" (Table 1), used in the calculation of required EEDI. The constant "c" for a container ship is less than half of the tanker "c". As "c" is the negative exponent, it has a substantial effect on the result. This systematic difference means that container ships have more margin to accommodate URN improving measures that reduce EEDI. All analyzed Aframax tankers have limited to no margin in their EEDI. The parameters "a" and "c" have been defined by the Marine Environment Protection Committee based on empirical data.

4. Analysis of URN of Tankers and Container Vessels with Respect to Individually Applicable EEDI Regulations

Underwater radiated noise from a large variety of ocean-going vessels was measured by underwater listening stations (ULS) on the west coast of Canada near Vancouver, BC. In this section, URN emissions of the vessel types "Aframax tankers" and "14000 TEU container vessels" are investigated for correlation with attained EEDI values as described in Section 3.The analysis consists of three steps:

a. Selection of suitable passages at similar operating conditions. This filtering minimized deviations due to factors other than the EEDI.

b. Correlation analysis between overall monopole source levels and EEDI requirements.

c. Analysis of dominant noise sources in URN.

This analysis facilitates estimating whether URN is dominated by noise sources that significantly affect energy efficiency of the vessel, in which case design modifications to fulfil EEDI requirements could also improve URN.

4.1. Methodology

Different analysis methods were applied for each of the three steps mentioned above.

Available vessel passes were filtered for best agreement of speed through water and reported vessel draft. This reduced the influence of vessel resistance, propeller operating condition, and required propulsion power on URN.

The analysis of correlation between URN and EEDI was based on monopole source level and EEDI attained for each individual vessel. Correlations analysis of URN with other parameters was not performed here, as this is dealt with in other projects such as the ECHO EVDI correlation study (MacGillivray et al. 2020).

Dominant noise sources were identified based on analyzing acoustic raw data in combination with metadata such as AIS logs and environmental conditions. The recordings were converted to spectrograms and spectra with different frequency resolutions and averaging durations. These results provided the following information:

- Spectrograms (e.g., Figure 6, Appendix A) combined with position data indicate directivity of sources and "acoustic closest point of approach". Time windows in which the vessel fore, centre, and aft pass the recorder is shown in the top panel of the spectrogram figures. Additionally, the travelled distance relative to closest point of approach (CPA, the minimum of the blue line equates to the position of AIS antenna) is shown (orange line) and the ship-hydrophone distance are shown for context. The DNV data window shows the time window that covers twice the length of the vessel to give an idea of the measuring geometry. The ANSI window shows the time that covers +/-30 degrees from the time of CPA. For very close CPAs, this duration can be very short. Information is applied for localizing the noise source and for identifying and differentiating contributions of the propeller and breaking bow wave. This works especially well for passages that were less than one vessel length, which included Tanker Afra 2 (see Figure 7).
- Relative band spectra of different averaging windows are used to quantify noise levels of the identified sources.
- Narrow band information is used to further differentiate tonal noise of engines and propeller. The results are summarized in tables by means of dominant sources within typical frequency bands.

Due to the small distance at CPA and the large size of the vessel, the vessel does not appear as a point source in the spectrogram. Individual noise contributors that are located at different length positions are clearly distinguishable as the vessel passes the recorder (Figure 6). Main engine and propeller contribute high source levels in a similar low-frequency range.

Note that the position of the evaluation window relative to bow and stern of the ship is not entirely consistent because the position of the AIS antenna was not exactly known and the time stamps for AIS data and acoustic data where not synchronized. However, as the propeller is recognizable clearly it is used as a reference to arrange the window position. This is not relevant for the conclusion from the analysis.

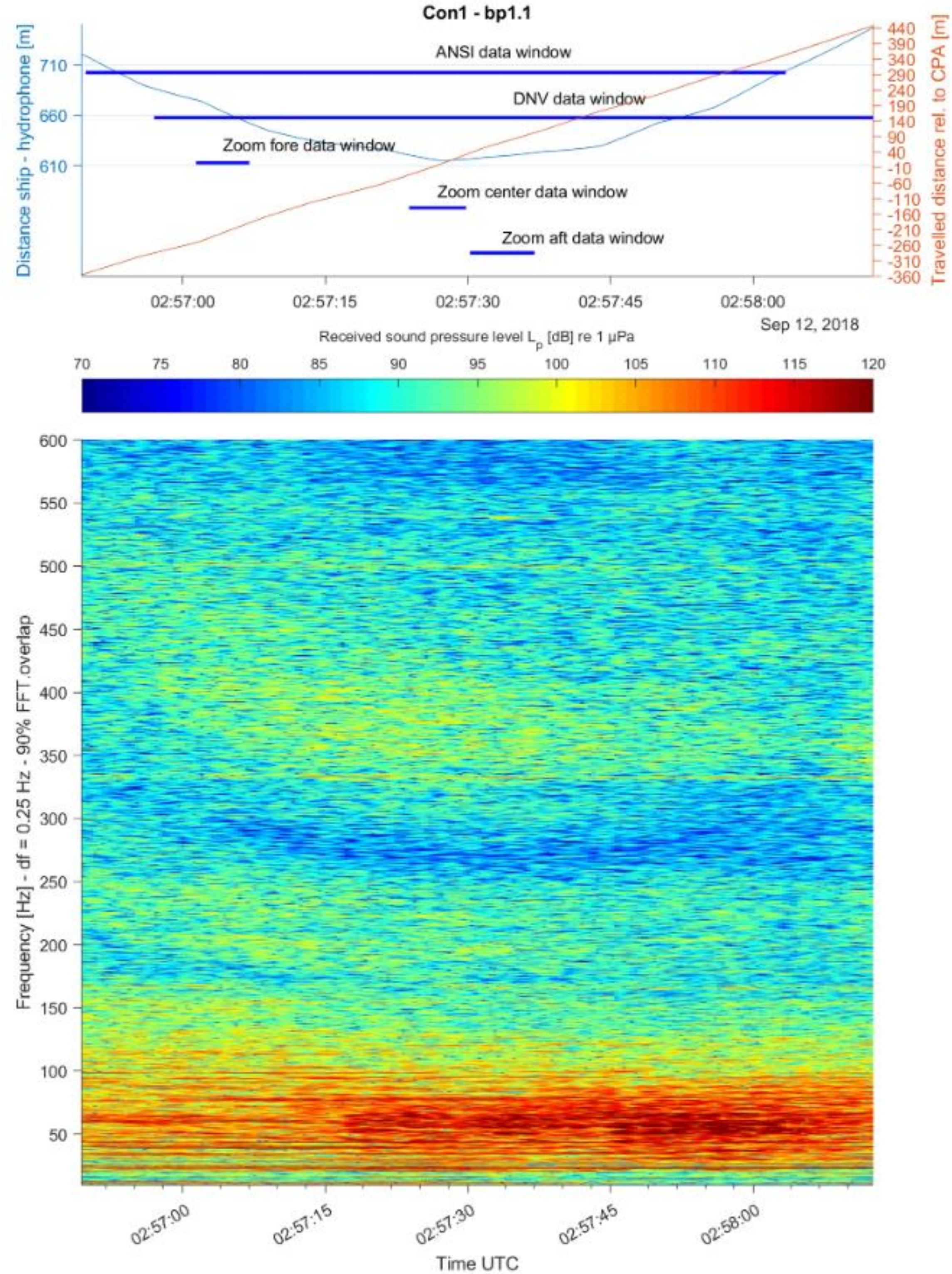


Figure 6. Example 1 of spectrogram analysis for identification of dominant noise sources of a 14000 TEU container vessel Con 1.

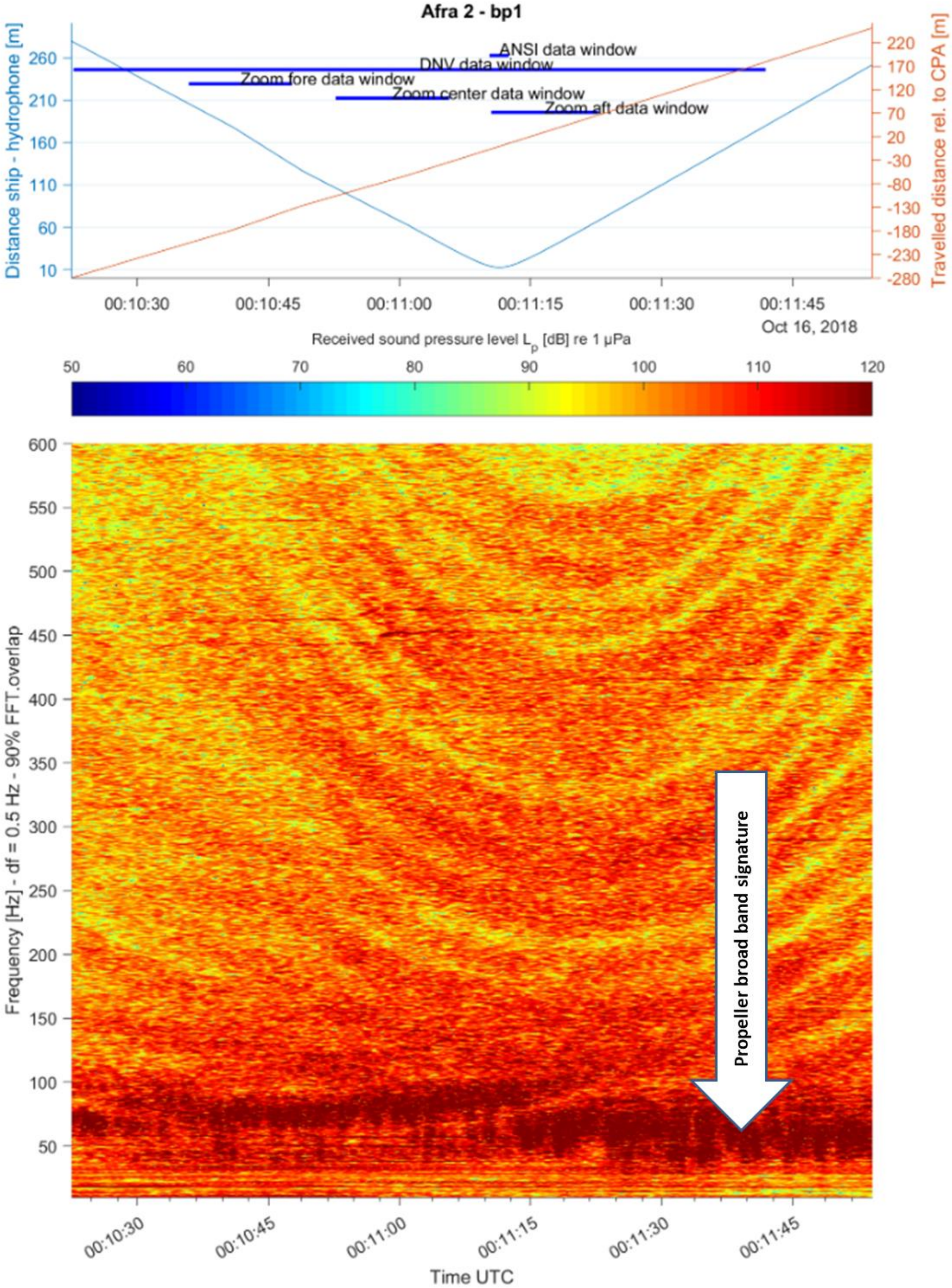


Figure 7. Example 2 of spectrogram analysis for identification of dominant noise sources of Aframax Tanker Afra 2. Spectrogram analysis figures for the remaining vessels are contained in Appendix A.

4.2. Pre-Post 2013 URN for 228–256 m Tankers at Vancouver-Fraser Port Authority

One vessel built before 2013 and one post-2013 vessel have been identified for this analysis.

Table 5 shows the Aframax tankers 1 and 2 that were considered for URN analysis. It allocates the calculated monopole source level based on the URN measurements. The category of post-2020 was not analyzed for URN as the vessel is not built yet.

Both vessels are similar with respect to design speed and deadweight. During the measurements, they were sailing at comparable speed but significantly different draft (Table 5). The post-2013 tanker has an EEDI value significantly below the required threshold. The tanker built before EEDI coming into force has an EEDI value that meets the threshold for those built after 2013. Therefore, it seems likely that technical differences between the tankers are linked to aspects other than EEDI.

Table 5. Overview of Aframax tankers with corresponding Energy Efficiency Design Index (EEDI) parameters, operating conditions, and attribution of dominant noise sources.

Vessel feature	Afra 1	Afra 2
Year built	pre-2013	post-2013
EEDI attained	3.69	3.32
EEDI required	-	4.32
Measurement parameters		
Design speed (kn)	14.5	16.1
Water speed (kn)	11.6	11.2
Ground speed (kn)	9.8	11.4
Closest approach distance (m)	230	40
Water speed / Design speed (%)	80	70
Vessel parameters		
Actual mean draft (m)	12.1	8.5
Max draft (m)	14.2	14.6
Actual mean / Max draft (%)	85	58
Overall MSL (dB re 1 µPa)	183.9	186.9
Acoustic sources		
Dominant 1–40 Hz	Main engine and propeller	Main engine and propeller
Dominant 40–80 Hz	Main engine and propeller	Main engine and propeller
Dominant 80–150 Hz	Main engine and propeller	Main engine and propeller
Dominant 150–1 kHz	Propeller and auxiliary engines	Propeller and auxiliary engines
Dominant 1–10 kHz	Propeller	Propeller

The overall monopole source level of the Afra 2 built after EEDI coming into force 2013 is 3 dB higher (6 dB higher contribution in low frequencies) than the overall monopole source level (MSL) of the Afra 1 tanker that was built before 2013. The attained EEDI of the Afra 2 is lower compared to Afra 1. Therefore, for the comparison of these two tankers the EEDI, improvement is apparently related to a higher URN level. An investigation of more vessels would be required to check whether this statement applies to a larger sample size. From the available data, no technical explanation can be drawn for the connection between radiated noise and attained EEDI values of the two tankers.

Note that beside the differences of load condition and speed also the CPA differs significantly (Afra 1: ~ 230 m, Afra 2: ~ 40 m). This large deviation of measurement geometry induces uncertainty for comparison of both recordings.

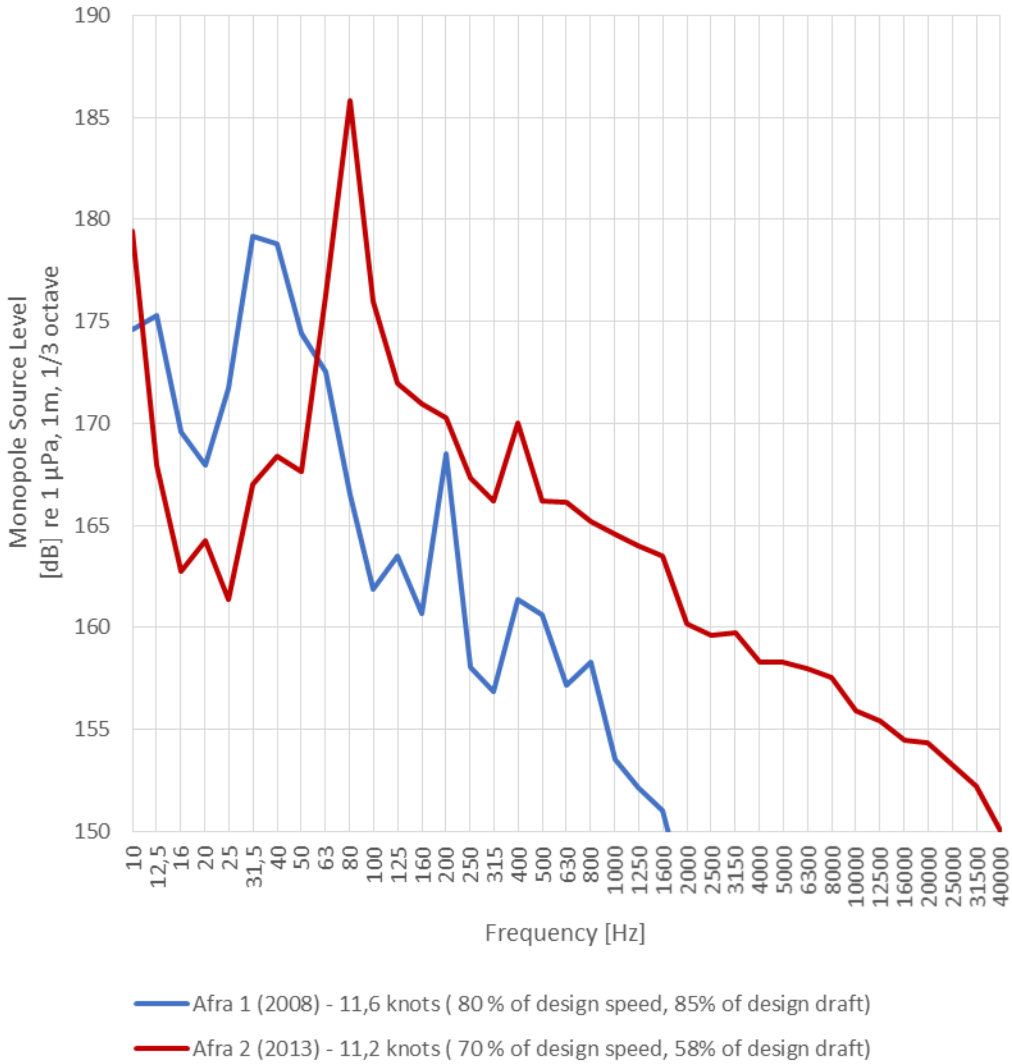


Figure 8. Comparison of monopole source level spectra of two investigated Aframax tankers The high level of Afra 2 in the 80 Hz one-third octave does not show as clearly in the spectrogram Figure 7. This is due to the use of the short ANSI window for the analysis, during which the 80 Hz was a dominant spectral feature.

4.3. Pre-Post 2013 URN for 14000 TEU Container Ships at Vancouver-Fraser Port Authority

Five 14000 TEU class container vessels were identified for this analysis. One was built in 2012, before EEDI came into force. The other four vessels are of the same design that needed to comply with the required EEDI thresholds for year 2013. The category of post-2020 vessels could not be analyzed, as no vessels have yet been measured and no designs were available from ship owners involved in this study. As an alternative, the four sister vessels were analyzed in parallel to show similarities and differences of individual vessels of a common design.

The details of the analysis are summarized in Table 6. Four of the five container vessels were sailing at similar speed between 80 and 84% of their design speed so that the relative comparison to EEDI is unaffected by speed variations. Only one vessel of the four was sailing significantly faster at nearly design speed. The draft was comparable for most vessels, as three of them were sailing between 91 and 97% of their design draft and two were sailing at 73 to 77% draft. With respect to correlation of URN with EEDI, attained EEDI values of all five vessels deviate by a maximum of 0.1%.

Table 6. Overview of 14000 TEU container ships with corresponding Energy Efficiency Design Index (EEDI) parameters, operating conditions, and attribution of dominant noise sources. N/A means the parameter was not available from the recorded data.

Vessel feature	Con 1	Con 2a	Con 2b	Con 2c	Con 2d
EEDI attained	9.20	9.19	9.19	9.19	9.19
EEDI required	-	16.050	16.050	16.050	16.050
Measurement parameters					
Design speed (kn)	25	21	21	21	21
Water speed (kn)	20	16.8	17.2	19.5	17.6
Ground speed (kn)	20.4	17.1	N/A	19.1	15.7
Water speed / Design speed (%)	80	80	82	93	84
Closest approach distance (m)	540	240	380	220	360
Vessel parameters					
Actual mean draft (m)	12	14.3	15.1	14.1	11.3
Max draft (m)	15.5	15.5	15.5	15.5	15.5
Actual mean / max draft (%)	77	92	97	91	73
Acoustic sources					
Overall MSL (dB re 1 µPa)	197.5	191.8	188.8	193.3	195.2
Dominant 1–40 Hz	Main engine	Main engine and propeller	Main engine and propeller	Main engine and propeller	Main engine and propeller
Dominant 40–80 Hz	Propeller	Propeller	Propeller	Propeller	Propeller
Dominant 80–150 Hz	Main engine and propeller	Main engine and propeller	Propeller	Main engine and propeller	Propeller
Dominant 150–1 kHz	Propeller and Aux	Propeller	Propeller and tonal (auxiliary engines?)	Propeller and tonal (auxiliary engines?)	Propeller and tonal (auxiliary engines?)
Dominant 1–10 kHz	Propeller	Propeller	Propeller	Propeller	Propeller

The five investigated container vessels show variation of monopole source levels in the range of approximately 8 dB although the deviation of EEDI are negligible. The analysis shows that the oldest vessel in this group is the loudest one, which can be linked to factors without any connection to energy efficiency.

The frequency analysis in Figure 9 indicates that the highest fraction of radiated noise of the pre-EEDI vessel "Con 1" is contained in the 31.5 and 50 Hz frequency range. These frequency bands are dominated by sound from the propeller and main engines. Most likely, the individual design of the propeller combined with the vessel's wake fields are relevant for the differences compared to the newer four vessels, which are sister vessels. This can be linked to varying design philosophies of different companies. Monopole source levels within the group of four sister vessels deviate up to 6 dB. In this case, tolerances, and specific operating conditions during measurements of the sister vessels lead to higher differences in URN than possible design requirements of pre- and post-EEDI vessels. Design issues and trade-offs are discussed in Section 5 .

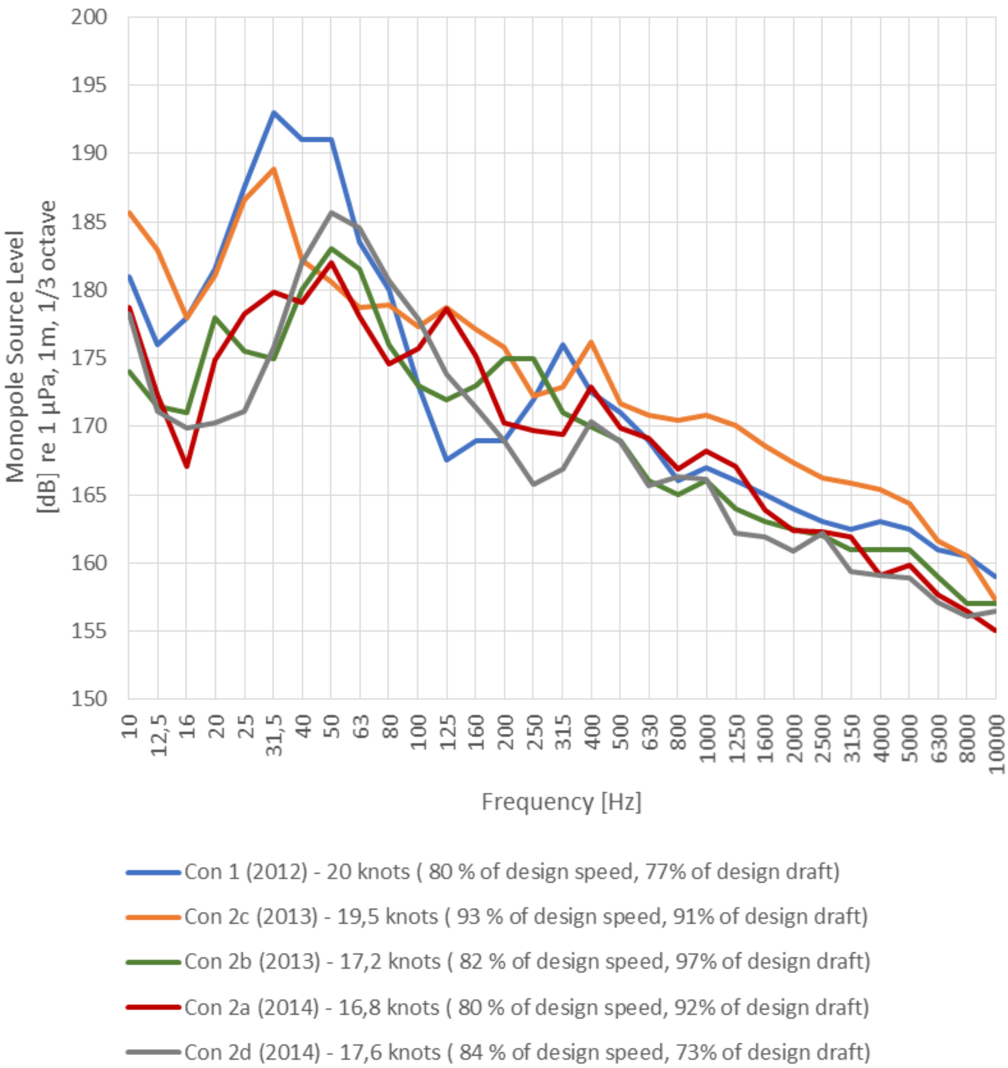


Figure 9. Comparison of monopole source level (MSL) spectra for the five investigated 14000 TEU container vessels

5. Propeller Design and Cavitation

The standard means of propulsion of seagoing vessels is the open, fixed-pitch screw propeller. The efficiency and URN issues associated with these propellers are discussed in this section.

5.1. Fixed Pitch Propellers

Propellers are designed for converting rotational power of the main engine into linear thrust to move a vessel forward (or decelerate backwards) through the water. For this purpose, the propeller is composed of multiple hydrodynamic profiles (Figure 10). A propeller functions like a wing or a foil: A pressure difference is induced between the suction side and the pressure side by accelerating and decelerating the flow (Figure 11). The difference of pressure acting on the area of the propeller disc generates a thrust force. Figure 12 illustrates the locations of the suction side and the pressure side.

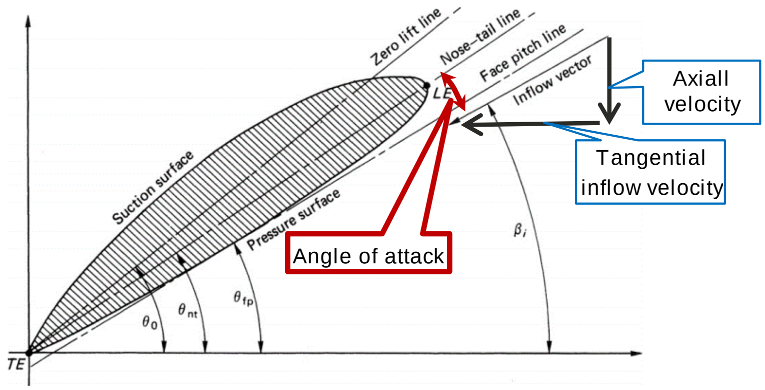


Figure 10. Definition of pitch angles and angle of attack. Source: Carlton (2012).

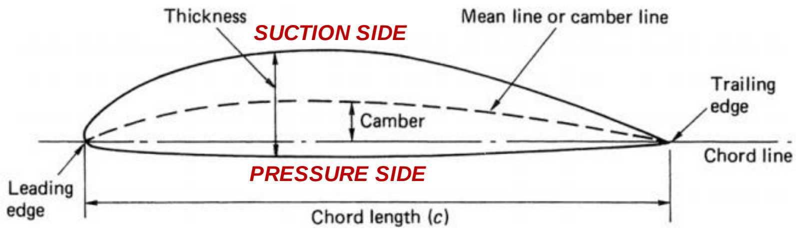


Figure 11. Characteristics of a hydrodynamic foil section. Source: Carlton (2012).

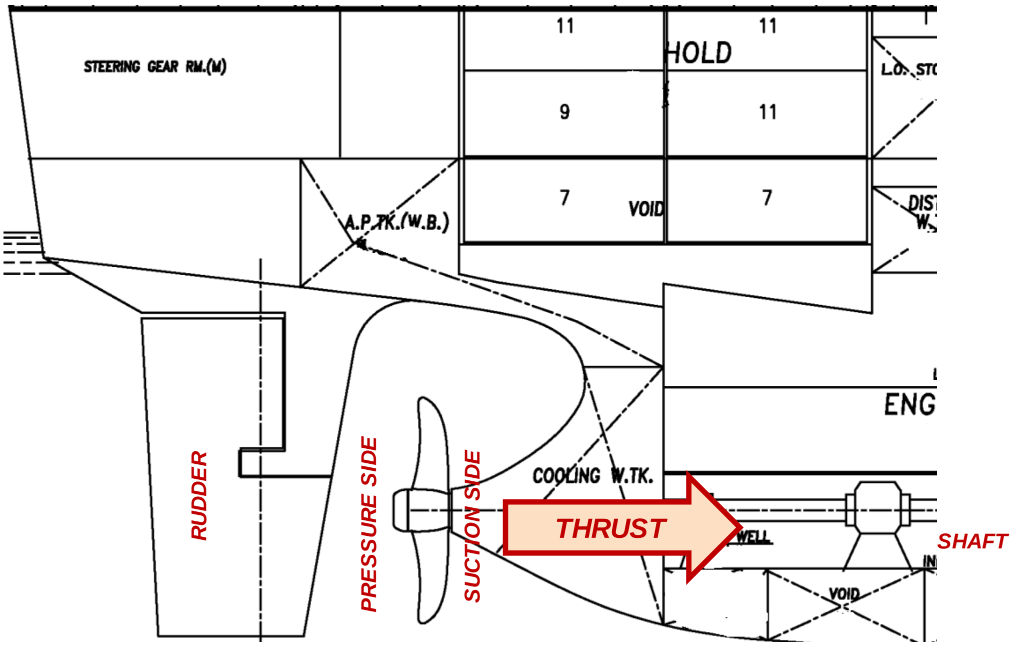


Figure 12. Sketch of suction side and pressure side, based on a typical general arrangement of a container vessel. Source: modified drawing of an unpublished general arrangement plan.

The propeller sections are inclined relative to the propeller plane, which is described by pitch angle. Lift is generated by the angle of attack of the profile relative to the combined inflow vector. Figure 10 shows how the propeller blades are exposed to axial flow due to forward motion of the vessel and to tangential flow due to rotation of the propeller.

The propeller can be described by a propeller disc encompassing all of the blades (Figure 13) where the ratio of projected propeller blade area onto the disc area is described by the blade area ratio (BAR). For blade area ratios greater than one, the blades overlap each other. Modern propellers are typically optimized for operation in a non-homogeneous flow (wake) behind a vessel's hull.

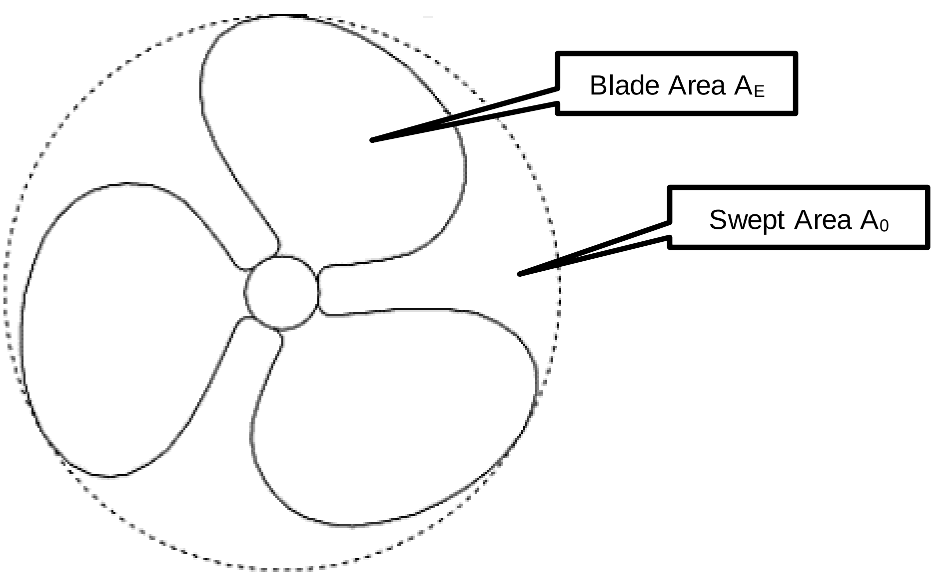


Figure 13. Description of blade area ratio (BAR) geometry. The propeller disk is the dotted circle that encompasses all the blade area and defines the Swept Area. BAR is equivalent to blade area/swept area.

5.2. Propeller Efficiency

The propeller is optimized for maximum propulsive efficiency in a given flow field (wake) behind the vessel. By far the dominating parameter for efficiency is the propeller diameter with the aim at minimizing relative loading, which is expressed by the thrust loading coefficient, C_{TH}.

This is defined as the ratio of the propeller thrust and the product of stagnation pressure and propeller disc area:

$$C_{TH} = \frac{T}{\frac{1}{2}\rho v^2 \frac{\pi}{4} D^2}. \quad (7)$$

where T is the thrust of the propeller, ρ, is the density of the water, v, is the flow speed, and D is the propeller diameter. In other words, it is preferable to create propulsive force by imparting a small acceleration on a large mass of water rather than imparting a large acceleration on a small mass. This is because the energy losses on the jet behind the propeller are proportional to velocity squared, and mass to the power of one.

C_{TH} relates very simply to the ideal efficiency (η) of a propeller. The ideal efficiency is one that only considers axial flow losses:

$$\eta = \frac{2}{\sqrt{1 + C_{TH}} + 1}. \quad (8)$$

There are additional losses due to friction of the propeller blades, vortices at the blade tips and hub, as well as in the rotating wake behind the propeller. In good designs, the real efficiency is 15 to 20 percentage points below the ideal efficiency. Figure 14 shows the ideal efficiency η versus C_{TH} and the efficiency of actual propellers. The propeller design is best when C_{TH} is close to 0.5 and efficiency is close to 75%. The dots in Figure 14 are the maximum efficiencies of real propellers.

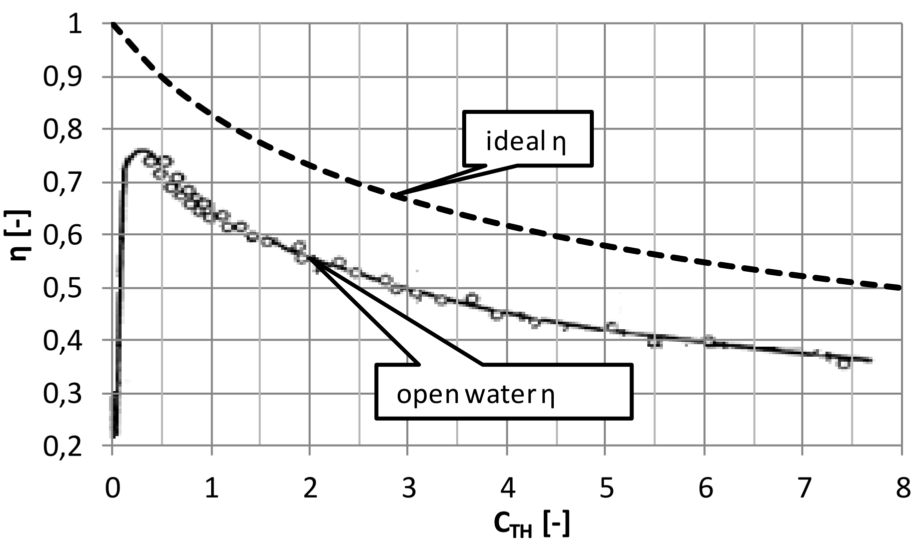


Figure 14. Ideal and open water efficiency (η) versus thrust loading coefficient (C_{TH}). Modified from Artjuschkov et al. (1988).

The efficiency variations of real propellers are not significant for a given thrust loading coefficient. In other words, the size of the propeller almost totally determines propeller efficiency. When propeller size is fixed, the vessel designer can influence efficiency by only about 5 percentage points by adjusting the shape to minimize the pressure fluctuation on the hull. Also note that for a given propeller size, efficiency increases if the vessel resistance (hence thrust) decreases.

The vessel designer therefore strives to have as large a propeller as possible. However, there are the following limitations on propeller size:

a. A vessel has a certain draft or draft range. The propeller cannot extend below baseline (or keel) and should not be out of the water too far at zero speed and still water (in ballast at low speed, this is usually accepted).

b. A large propeller turns more slowly than a smaller one. When power is applied at a lower RPM, torque increases. This torque must be provided by the main engine, which grows in size because engine size is driven by torque rather than RPM. Engine makers introduced low-speed long-stroke engines to minimize RPM.

Often the sum of all vessel constraints leads to propellers that do not have the lowest C_{TH}. Vessels with draft limits as used in inland waterways have very small propellers with an efficiency of 50% or less. This loss of efficiency is visible in Figure 15 for propellers with low pitch (P/D) values that rotate quickly due to the low P/D ratio (P/D is the pitch/diameter ratio; pitch is the path a propeller would move forward in one revolution similar to a mechanical screw). J is the advance ratio $J = \frac{v}{nD}$, where v is the water inflow velocity, n is the propeller revolutions per second, and D is the propeller diameter.

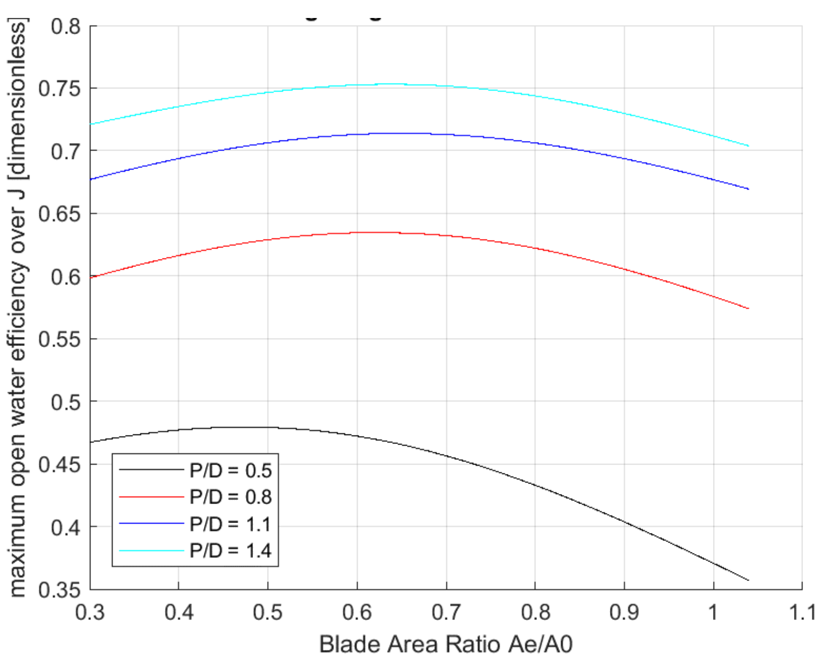


Figure 15. Maximum open water efficiency as a function of blade area ratio, shown for different pitch/diameter (P/D) ratios. Source: calculated according to Oosterveld & van Oosanen (1975).

The efficiency discussed here is the open-water efficiency, i.e., the efficiency of a propeller in a uniform flow. However, the propeller operates behind a vessel that creates variations of the inflow speed (wake field). In a single screw vessel at the top (12 o'clock) position, water is "pulled" forward by the vessel so the propeller may see an inflow that is half the speed of the vessel and has high variations in the angle of attack on the blade profile.

The wake tends to improve overall efficiency because the propeller operates in a flow that is slower on average than the vessel, reducing the v parameter in Equation 7). This leads to better overall efficiency because the Thrust reduces with v^2. This effect is described by the wake fraction that expresses the percentage of deviation of the average flow into the propeller compared to vessel speed and the wake's uniformity. The most favourable conditions in this respect are found in single screw submarines, where propulsive efficiency can exceed 85%, i.e., 10 percentage points above open-water efficiency. In good single screw surface vessels, the improvement in efficiency may be 2 to 5 percentage points. In twin screw vessels with open shafts, this value is lower.

The propeller designer compensates for wake field variations by designing the pitch to an average value found along each radius of the propeller disc. The pitch is not optimum in areas of undisturbed wake because it must account for the decelerated inflow in limited sections of the wake field.

5.3. Propeller-Induced Noise and Vibration

As shown in Figure 10, the effect of slower inflow into the propeller (higher wake) is an increase in the angle of attack, Figure 16 the right hand side of the figure shows the condition at top position of the propeller disk . This results in reduced pressure on the suction side of the propeller, which leads to cavitation (local pressure becomes lower than vapour pressure; Figure 17).

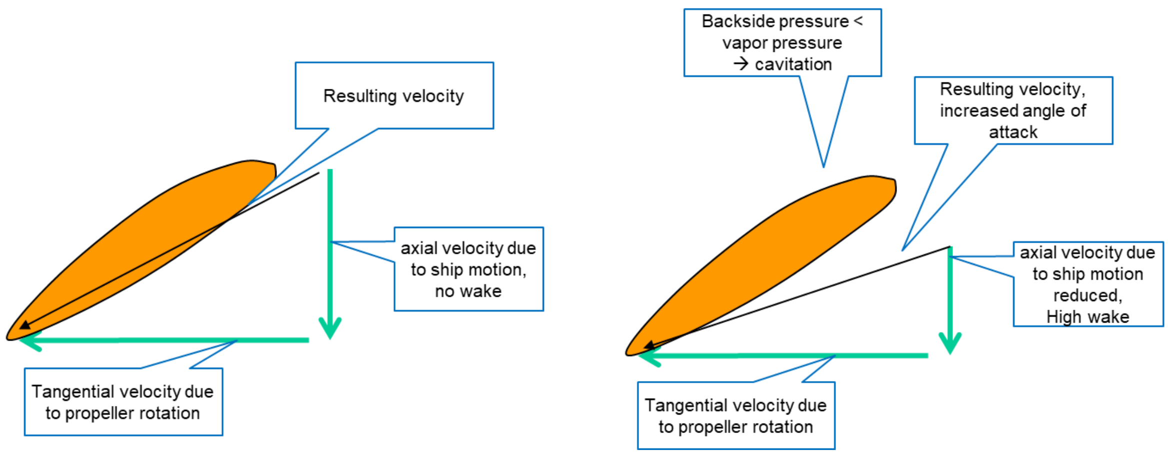


Figure 16. Change in flow velocity and angle of attack in different axial velocity due to wake variations. Left hand side describes the case of high axial inflow velocity, right hand side shows the effect of lower axial velocity.

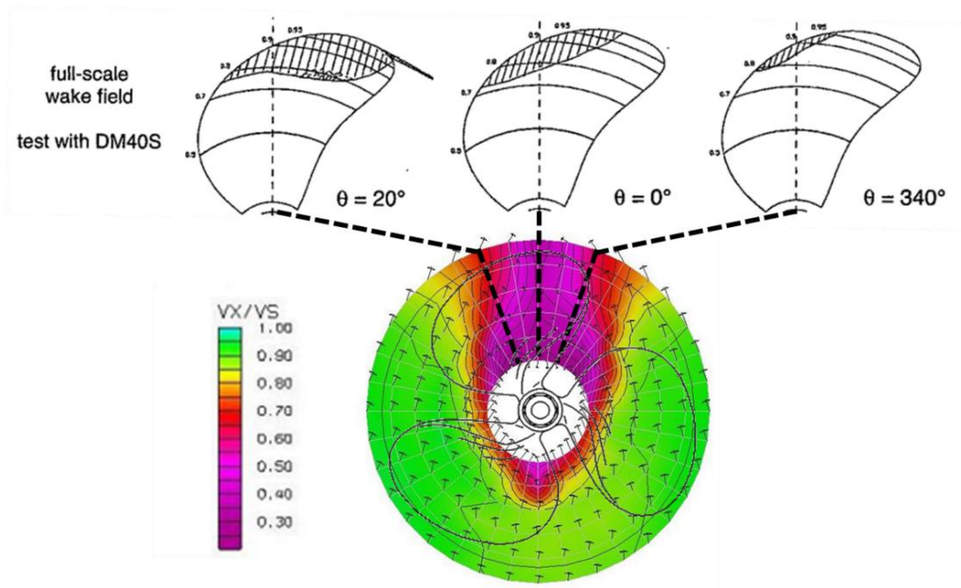
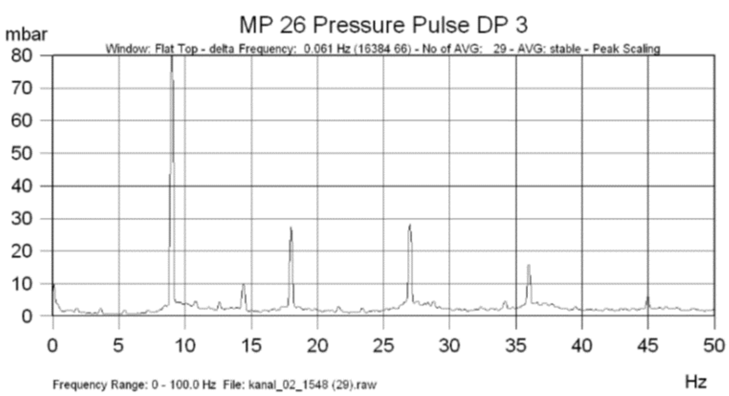


Figure 17. Wake field and cavitation pattern. A sheet cavitation bubble is shown developing on the suction side (forward facing side of the blade) while passing through a region with high wake (low axial velocity VX into the propeller; purple area: VS = ship speed). Green denotes areas of the flow field that are undisturbed by the vessel. Source: Compilation of Fahrbach (2004) and unpublished HSVA report.

Cavitation is the dominant sound source of a vessel transiting close to service speed. The gas-filled bubble that develops during cavitation subsequently collapses, which constitutes a strong monopole sound source. The bubble appears at each blade passage, which is the shaft rotational frequency multiplied by the number of blades. Because the process is not sinusoidal, there are multiple harmonics of blade rate present in the resulting spectrum (Figure 18).

The most prominent effect of these mechanisms are pressure fluctuations on the hull above the propeller, which cause vessel structures to vibrate, which has acceptable limits based on Classification Society requirements. Limiting the vibration levels has an influence on the propeller design directed to limit the extent of cavitation.

Figure 18 is a classical display of pressure fluctuations on the vessel hull above the propeller where pressure is presented in linear units (milli-bar; where 1 bar = 100 kPa). Here the blade passing rate is at 9 Hz, and there are peaks visible up to the 5th harmonic. The spectrum looks 'clean' with no contribution at frequencies between blade rate tonals. The display ends at 50 Hz because there is no effect on vibration beyond 50 Hz.



Shaft Speed 108.0 1/min

Freq. [Hz]	Order	bar
0.06	0.03	0.01
8.97	4.98	0.08
10.80	6.00	0.00
14.40	8.00	0.01
18.01	10.00	0.03
26.98	14.99	0.03
27.59	15.33	0.00
28.81	16.00	0.00
34.24	19.02	0.00
36.01	20.01	0.02
44.98	24.99	0.01
54.02	30.01	0.01
61.40	34.11	0.01

Figure 18. Pressure fluctuations of propellers measured at the hull. Source: Germanischer Lloyd sea trial measurement report (2008), anonymized and unpublished.

However, when viewed with a pressure axis in dB typically used for acoustics, the data in Figure 18 has substantial energy between the tonals (Figure 19). This energy likely arises from stochastic variations as the bubbles created never look the same with each blade passage; the exact mechanisms are unknown. Interestingly, the spectrum measured far from the vessel often lacks the tonal peaks at the blade passing rate (red curve in Figure 19).. The Spectrum with a maximum around 40 to 50 Hz looks similar for almost all single screw ships with a fixed pitch propeller. There is currently no scientific explanation for this.

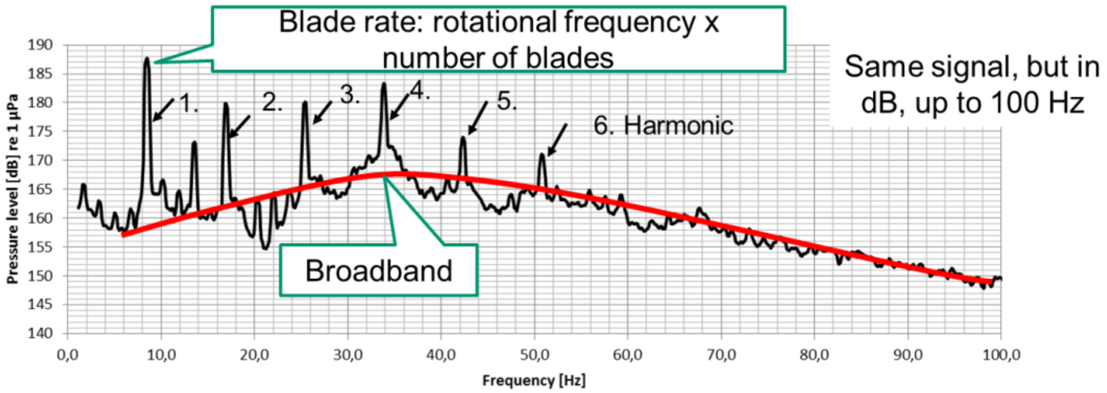


Figure 19. Same data as Figure 18 with the vertical axis as sound pressure level rather than pressure. The numbers shown indicate the harmonic number. Source: DW-ShipConsult instructional data.

For this study, it is reasonably assumed that reducing the level of the first blade rate harmonic also reduces the broad band level. There is, however, no validation of this hypothesis, and there are mechanisms that lead to strong levels at frequencies other than blade rate (see Section 5.4).

5.4. Designing to Reduce Cavitation

The propeller designer must limit cavitation to limit vibrations as required by the Classification Societies. The following are the factors available to the designer:

- Ensure a "good" wake field. This is positive for efficiency as well as for low URN and vibration. However, there is no common definition of what is good. For a possible approach see Section 5.6.
- Adjust the propeller to the wake field. One of the main parameters is propeller skew. This is also positive for efficiency and for URN and vibration. However, reports on high-skew propellers and the effect on cavitation show that cavitation can be reduced in extent and delayed. Applying these measures may have other possible effects such as unstable cavitation, which may lead to greater URN, vibration, and onboard noise levels at higher harmonics of blade rate.
- Relieve the blade tips, i.e., reduce pitch at the tips to minimize cavitation effects at 12 o'clock, and reduce creation of tip vortex cavitation. This is a vital factor to control cavitation inception and push it to higher speeds. In case of a low-speed range, the difference of pitch distribution will bring a meaningful difference of cavitation and hence URN. In practice, propeller designers optimize the pitch distribution to balance efficiency, vibration, and erosion risk. A central part of these designs is the tip unloading (low pitch at the tip). This is a typical solution to delay cavitation inception and practiced in many vessels designed to acoustic specifications (e.g., research vessels, ferries, military vessels). The tip unloading design can easily be adopted in these cases because their wake variations are usually moderate. Many kinds of merchant vessels have a steep wake peak that reduces the effectiveness of tip unloading. In such cases, tip unloading designs tend to lead to cavitation erosion problems (i.e., the propeller materials are damaged by the cavitation). If the pitch is too small, negative angles of attack may occur in 'good wake areas' which leads to pressure side cavitation, which must be avoided as excessive pressure side cavitation leads to erosion of the blades. This

measure harms efficiency because the outer regions of the blades contribute less to thrust but retain the same friction losses.

- Increase blade area ratio that distributes suction pressure over a larger blade area with smaller peak pressures. Because of the larger area exposed to water, this reduces efficiency as shown in Figure 15.

No systematic investigation of the relationship between efficiency and URN has been published yet.

5.5. Cavitation and Noise

There are multiple ways of generating noise in cavitation, with different effects at different frequencies. For the moment, we concentrate on frequencies below 300 Hz, which are responsible for high levels of URN attributed to worldwide shipping. As mentioned in Section 5.3, the radiating mechanism of the sheet cavitation bubble is that of a monopole. Figure 20 shows the measured sound pressure level above the propeller for a 3600 TEU container vessel for different RPM.

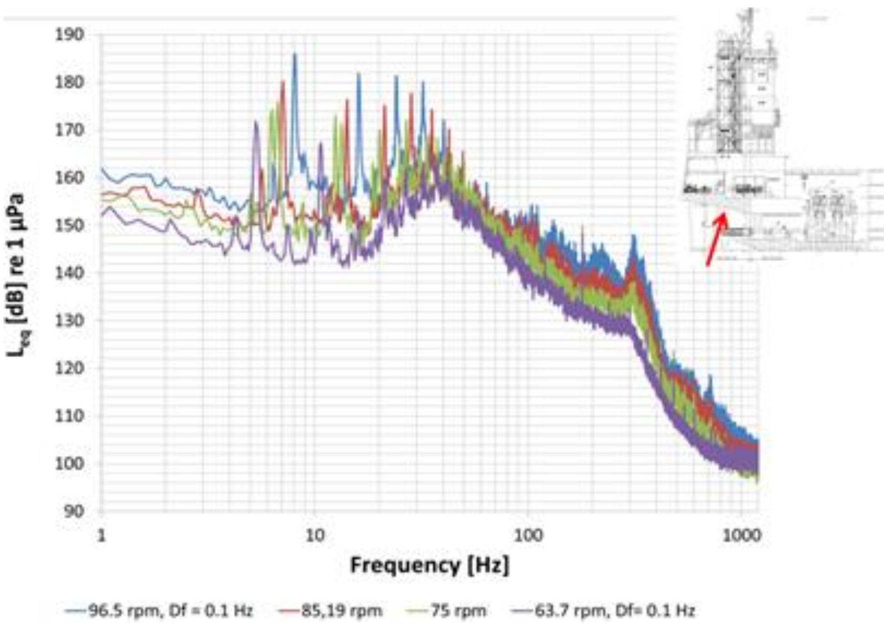


Figure 20. Sound pressure level (SPL) measured at hull above propeller at various speeds. Source: Wittekind and Schuster (2017)

Radiation of an oscillating monopole far from any boundaries follows:

$$p(t,r) = \frac{\rho V''(t)}{4\pi r}, \quad (9)$$

where p is the sound pressure, ρ is density, V'' is the volume acceleration, r is the distance and t is time.

Using the pressure of the time signal of Figure 20 and averaging over multiple blade passages, the actual cavity volume and associated pressure can be calculated (Figure 21). At high volume acceleration (≡ high curvature in the volume graph), sound pressure peaks. Mitigation is possible if the volume graph (Figure 21) could be smoothed to decrease curvature of the volume graph.

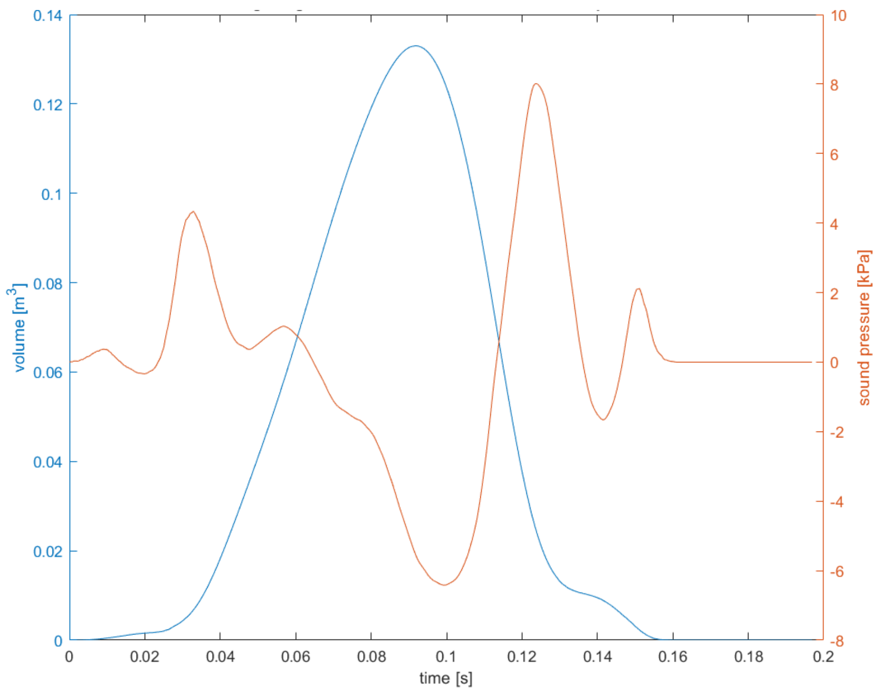


Figure 21. Bubble cavity volume and sound pressure of cavitation. Source. Unpublished research, University of Applied Sciences Kiel and DW-ShipConsult.

5.6. What is a "Good" Wake Field?

Propeller design is driven by rigid limitations; however, optimizing inflow to the propeller (wake) is a design parameter of interest when exploring opportunities of concurrent acoustic and efficiency improvements. While the propeller designer invests substantial effort to find the minimum unloading (low pitch) level that optimizes efficiency, URN, and erosion risk, the actual performance of the propeller depends greatly on the vessel wake distribution that arrives at the propeller. The differences in URN measured for ferries with different trims at the same draft are evidence of the significant effect that the wake field has on URN (MacGillivray et al. 2020).

Optimization of wake fields to improve propulsion and URN requires a criterion for the quality of the wake field. One obvious criterion is the wake variation along the circumference at each radius, and another is the gradient of wake. This was investigated in a master thesis in 2004 (Fahrbach 2004). The criterion assigns high ratings if the variations of wake along circles at different radii show a minimum of variations. Figure 22 shows the best and the worst wake field in the study.

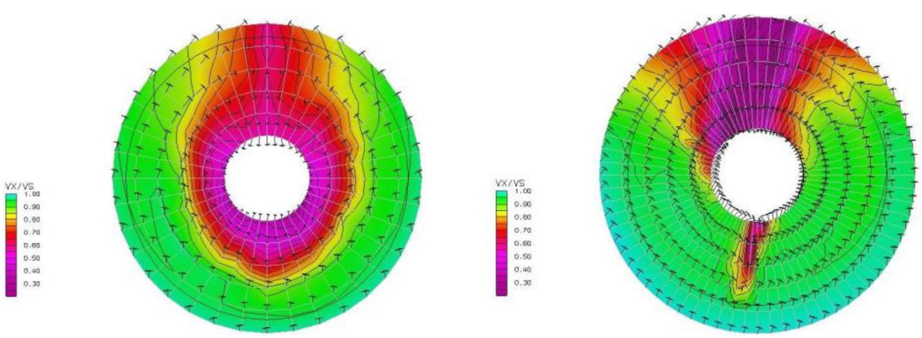


Figure 22. (Left) A "good" wake field and (right) a "bad" wake field. Source: Fahrbach (2004).

The relationship between wake fields and pressure pulses in cavitating conditions were investigated by Fahrbach (2004) using computational fluid dynamics calculations. The results are summarized in Figure 23, showing the connection between the quality ratings of wake fields to pressure pulses at blade rate observed. The variations in calculated pressure pulse amplitudes with the rating are obvious. Note that a value of 5 kPa for tankers is at the edge of acceptability to ensure acceptable vibration levels onbaord.

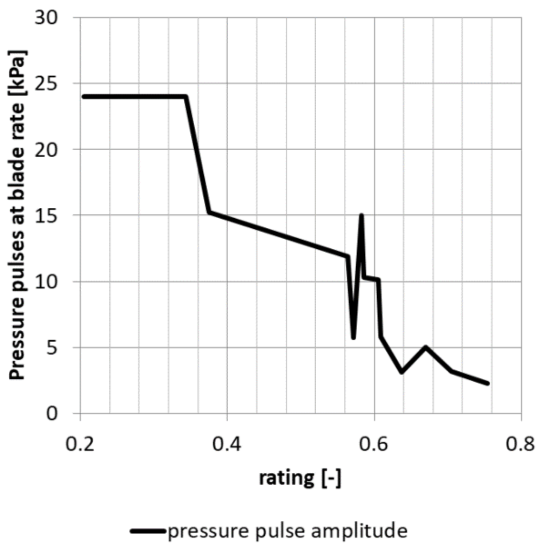


Figure 23. Wake field rating versus pressure pulses. Source: Fahrbach (2004).

5.7. Optimizing Vessel Form and Propulsion in Unison

Blunt vessels, i.e., those with a high block coefficient such as tankers and bulk carriers, are the most difficult to design for a good wake field and good propulsions characteristics. These vessels are slow and are designed for minimum friction resistance, while wave making resistance is of minor importance. To minimize friction resistance, the wetted area (the area subjected to the flow around the vessel) is minimized, which leads to a short wide vessel with a long parallel body section. The block coefficient may exceed 0.8, which means the vessels are 20% away from a rectangular box of length × breadth × draft.

There are several ways of designing such vessels. One way is to find a good hull shape (i.e., low towing resistance) and then match a propeller to this shape, which means adapting it to the resulting wake field. The second way is to compromise the hull form with a good wake field, which ensures good propulsive efficiency and low vibrations while sacrificing some of the towing resistance. Figure 24 shows the resulting hull shapes for both ways. Of course, the shapes in Figure 24 are grossly exaggerated for clarity.

It is expected, though not verified, that a design of the hull and the propeller together would improve overall efficiency by a few percent but with a leap in reducing pressure pulse amplitudes and vibration extent.

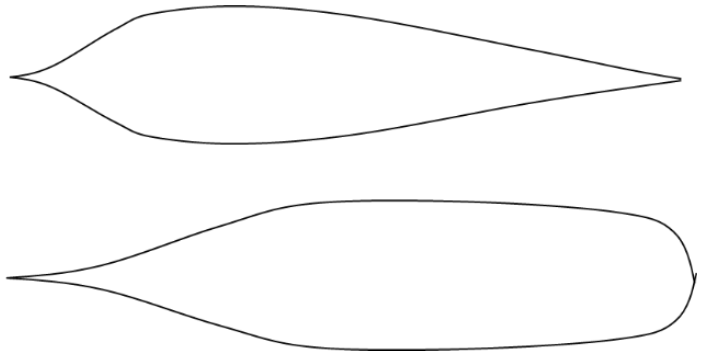


Figure 24. Two hull forms with (top) low resistance and (bottom) good propulsion. Flow is from the right hand side.

5.8. Effect of Speed on Propeller Design

With a vessel designed for lower speed e.g. a tanker vs. a container vessel, the hull form is blunter (i.e. has a higher block coefficient) and therefore comprises a more difficult wake field. The propeller is always designed for maximum efficiency keeping vibration caused by cavitation below the limits imposed by the Classification Societies.

For various reasons operational vessel speeds have reduced in the past years. Consequently, new vessels are designed for lower design speeds expecting that the previous high speeds will not be required in the future.

Older vessels designed for high speed now operate at low operational speed (e.g. 25 knots vs. 18 knots for a container vessel: called slow steaming). In this situation the vessel is significantly quieter than at design speed; however, as operators expect the economic situation to prevail, they change propellers to optimize for the lower speed. The propeller will have a lower BAR and lower pitch reduction at the tips and consequently very similar cavitation behaviour as the propeller for high speed. In other words, the vessel with a propeller designed for 25 knots operating at 18 knots will have a lower URN than the vessel with a propeller designed for 18 knots and operating at 18 knots. We can expect some lower URN nevertheless because power driving the propeller has reduced but this is difficult to quantify.

5.9. Case Studies

5.9.1. Effect of Variations of Propeller Blade Skew

A study by the Hamburg Ship Model Basin (HSVA) investigated the effect of different blade designs (HSVA 2007). The design parameter studied was the skew angle of the propeller blades. The skew angle is defined by two lines passing through the hub centre to the most forward position of the mid-chord line and the position of mid-chord at the blade tip (Figure 25).

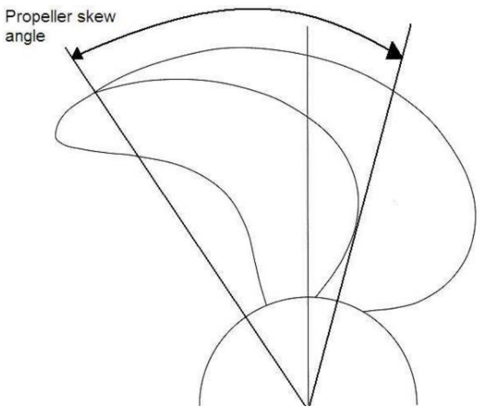


Figure 25. Definition of propeller skew angle. Source: HSVA (2007).

The idea behind skewing is that the leading edge of the blades does not pass through a wake variation at the same circumferential position, which stretches the expansion and collapse of the cavitation bubbles. Observations indicate that while high-skew propellers increase cavitation inception speed, once cavitating they show tendencies toward unstable cavitation. This would result in URN components at higher frequencies and in broad band, even if the levels at blade rate are reduced. It may, therefore, not be justified to assume that URN at all frequencies varies in the same way as the blade rate tonal when skew is varied.

For this investigation, an existing propeller design at following vessel conditions was used:

- 18,320 kW delivered power,
- 107.7 RPM shaft speed,
- 35.5% D propeller tip clearance and
- 22.05 kn vessel speed.
- The investigation was made using HSVA's CFD prediction model, which is validated by a large number of model test results (HSVA 2007).

The basic model propeller was tested in HSVA's model basin. For this existing propeller design, a variation of skew angles was calculated. Figure 26 shows the skew variations. Figure 27 shows the results of skew variation calculations. Increasing the skew angle from 0% (18°) to 200% (about 55°) reduces the first harmonic of the pressure pulses by about 25% (equivalent to about 2 kPa). With that, the propeller efficiency decreases by less than 1%. Reducing pressure amplitude by 25% is equivalent to a 2.5 dB URN reduction.

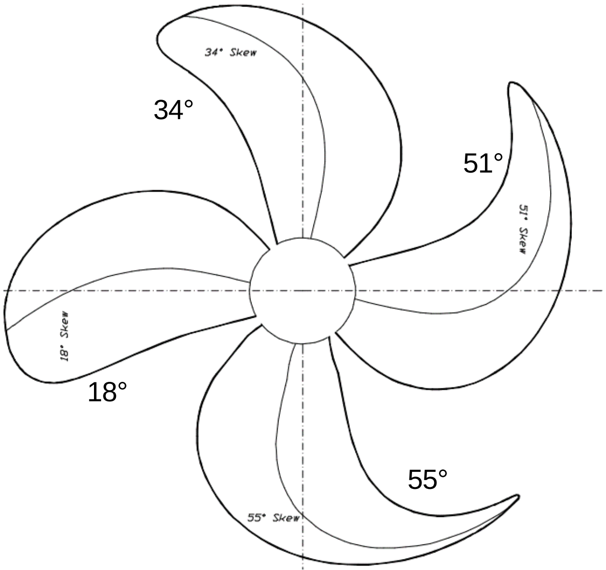


Figure 26. Propeller skew angle variations to investigate skew influence on efficiency and pressure pulses. Source: HSVA (2007).

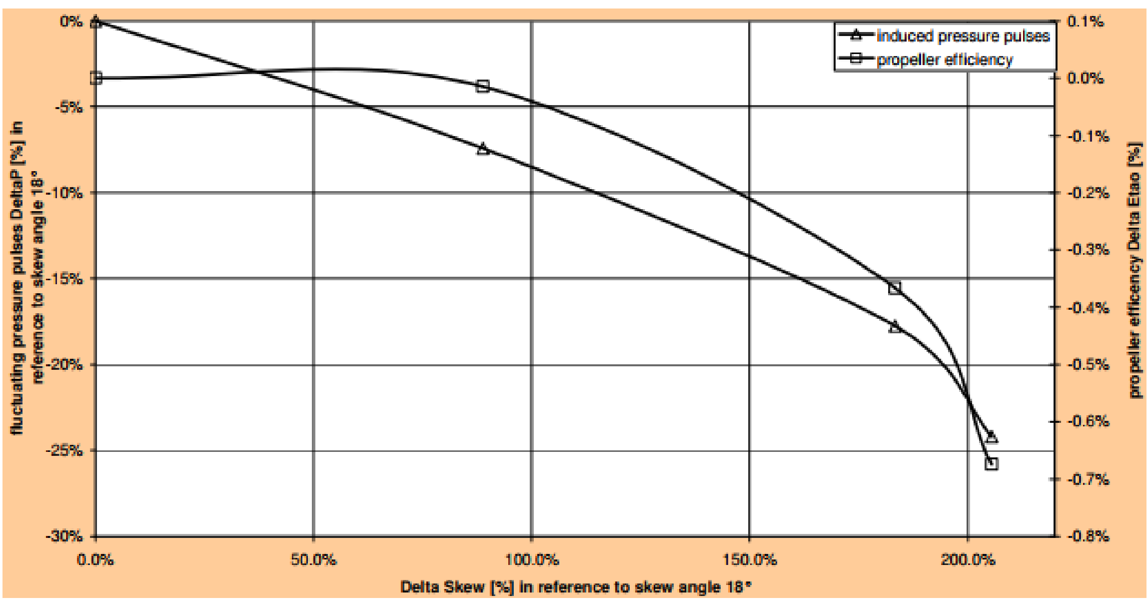


Figure 27. Variation of the propeller skew and resulting induced pressure pulses and propeller efficiency (by calculation). Source: HSVA (2007).

5.9.2. Variation of Pitch Distribution

HSVA (HSVA 2007) investigated Propeller pitch distributions by keeping the propeller propulsion performance constant and optimizing the propeller pressure fluctuation pulses. The calculations were done for the same main vessel conditions given in Section 5.9.1. The two propeller designs differ only in pitch and camber distribution. Pitch is a measure the distance one rotation of the propeller would move the ship forward if there were no slippage and depends on the angle of attack of the blade profile to the inflow resulting from superposition of tangential velocity of the blade and the flow behind the vessel. Camber describes the curvature of the blade profile. Figure 28 shows the tip unloading of propeller 1 compared to propeller 0 due to the modified pitch variation. The open-water efficiency (Figure 29) could be increased in this vessel operation condition by about 1%. Figure 30 presents the reduction of the first harmonic by 1.7 kPa (equivalent to reduction of 3.3 dB). In the most cases, this goes along with an increase in at least the second order harmonic, which amounts in this case to about 1 kPa (HSVA 2007).

It is difficult to safely predict whether the broadband URN would also decrease in the same way with this change. The increase of levels at higher harmonics is an indication against this possibility.

The observation that pressure pulse levels decrease but efficiency also increases contradicts most other observations, which show lower efficiency with lower pressure levels. So, in this case, the effect that both parameters improve may be attributed to a generally more careful design of the second propeller. In any case, we expect that the amount of change in level is representative of what could be expected by optimizing the blade properties such as camber and pitch along the span. For a given vessel and starting from a reasonably good design, the improvements will be a few decibels rather than 10 dB.

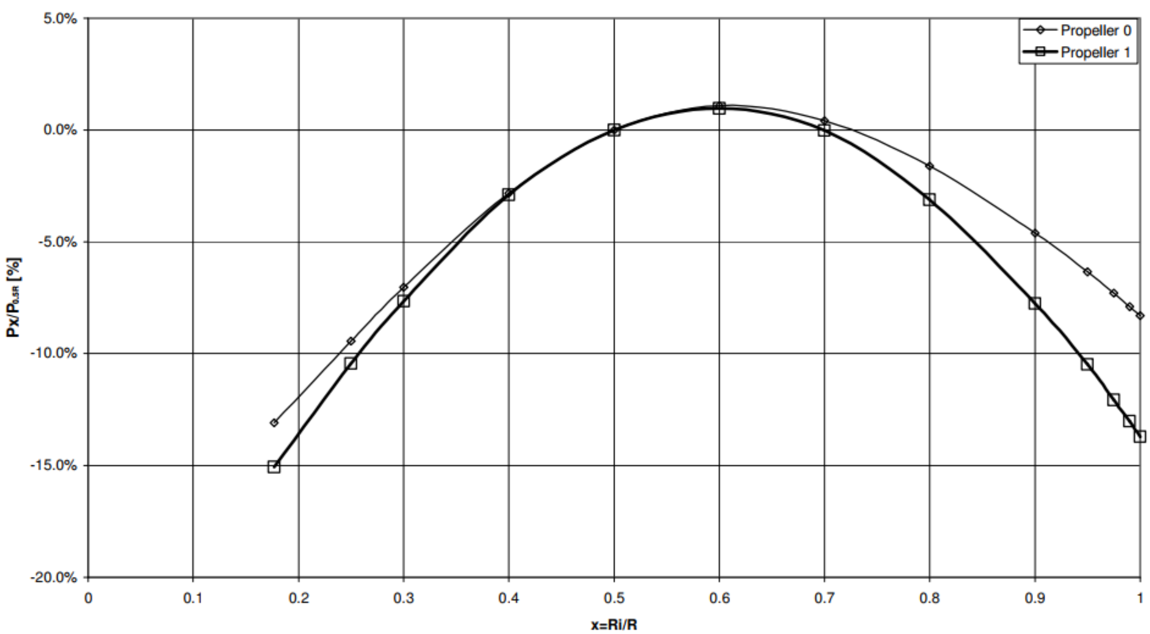


Figure 28. Variation of pitch over propeller radius for an original propeller (0) and a modified propeller (1). Pitch of propeller 1 s substantially reduced at the blade tips close to r = 1. Source: HSVA (2007).

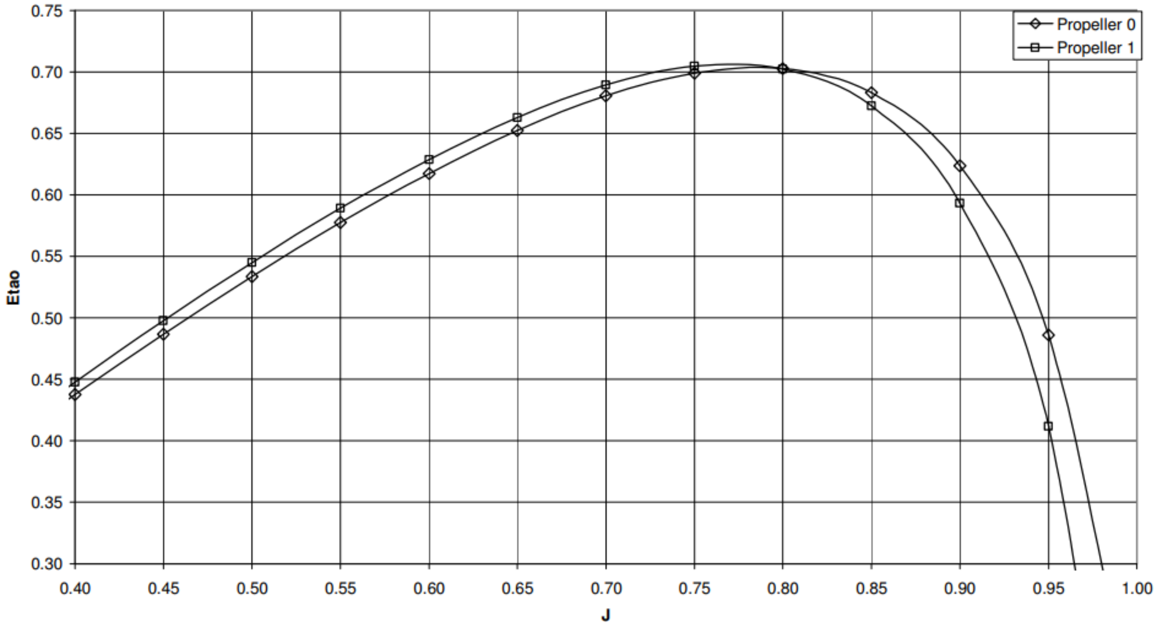


Figure 29. Open water efficiency for an original propeller (0) and a modified propeller (1). Source: HSVA (2007).

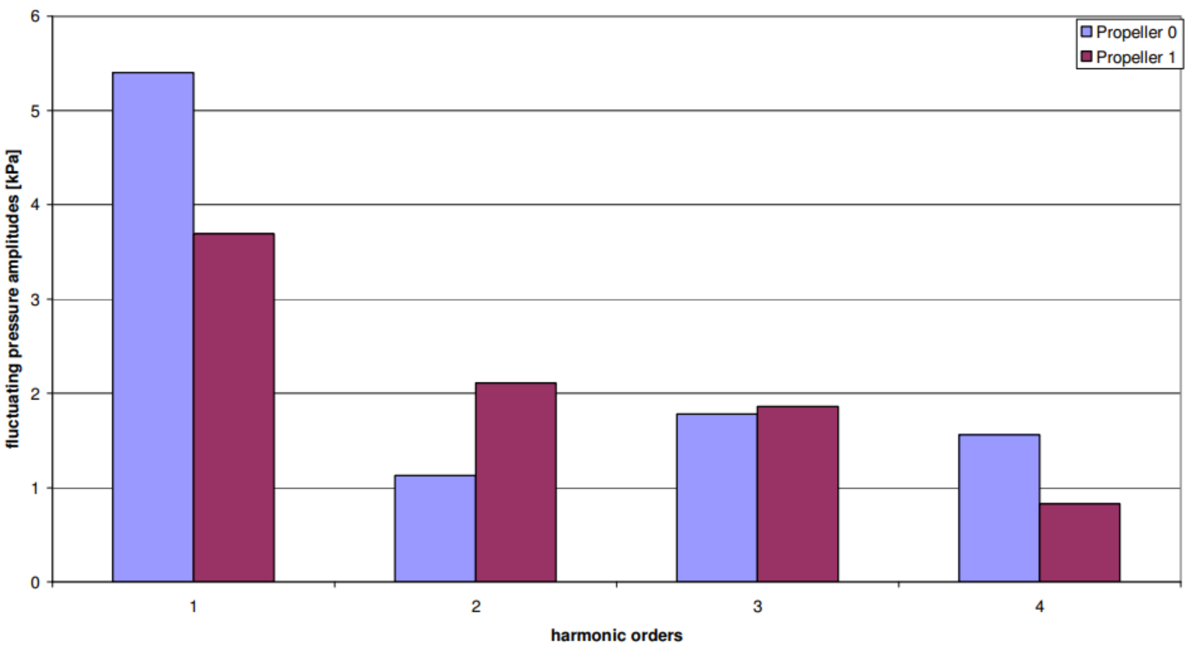


Figure 30. Pressure amplitudes at blade rate harmonics for an original propeller (0) and a modified propeller (1). Source: HSVA (2007).

5.9.3. Variation of Blade Area Ratio

The remaining and dominant controllable design parameter for decreasing cavitation and URN is the Blade Area Ratio (BAR). Increasing the BAR tends to reduce the suction pressure, which increases the cavitation inception speed. In case of a large blade area the pressure is distributed over the larger area with reduces peak pressure. Unfortunately, increasing the BAR leads to reducing efficiency by increasing friction (between the water flow and the propeller blades). This can easily become considerable and would not be tolerated by vessel operators or regulating bodies. Even a low-level trade-off between propeller URN and efficiency would lead to a high cumulative fuel consumption of the vessel in its total life. Inherent fuel costs and CO_2 emissions would negate any positive acoustic gains in this respect. Large BAR also leads to heavier propellers. Propellers are sold by their weight so this propeller becomes more expensive by a few tens of thousand US dollars depending on size. This is not easily accepted by shipyards. Together these factors mean that BAR adjustment must be analyzed very carefully.

5.9.4. Change of Wake Field Due to WED

Wake equalizing devices (WED), such as ducts and pre-swirl stators, smooth a vessel's wake and permit a more unloaded propeller design (low pitch at tips). WEDs are installed to increase efficiency, but observations also indicated improved vibration behaviour. This result is anecdotal; a dedicated study of them is needed.

The following is a description of the application of a Mewis duct WED designed by Becker Marine Systems (BMS), Germany. Figure 31 shows a typical installation.

Figure 31. Typical installation of a Mewis duct wake equalizing devices (WED).

The duct consists of a nozzle with several fins at the inside. This arrangement is a custom design adapted to the individual wake field of a vessel. The duct changes the inflow to the propeller resulting in a more uniform inflow and pre-swirl. The improvements demonstrated are between 3 and 8% in terms of reduction of fuel consumption. The improvements are greater for vessels that were less efficient before the application of the duct.

Figure 32 is a wake field of normal quality of a modern single screw vessel. It shows the colour coded axial inflow velocity to the propeller, green means the flow speed is the same as vessel speed. Purple is one half of the vessel speed. The arrows indicate the flow direction. The flow around the top position is retarded because it is partly obscured by the hull in front of it. The flow direction is generally from bottom to top.

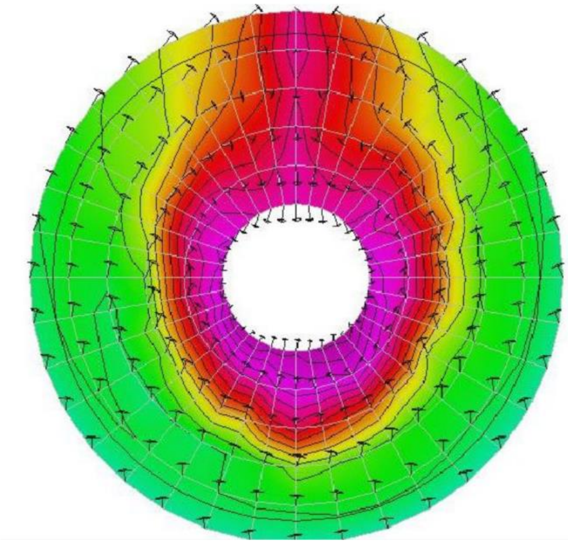


Figure 32. Wake field of a single screw vessel. From Fahrbach (2004).

The propeller turns clockwise in the wake field in Figure 32. The propeller blades on port side (left) move upwards with the inflow. The blades at starboard side move down against the upward inflow. Around the top position, the inflow is small and the angle of attack on the blades is large. This means the propeller blade sees different conditions in term of inflow speed and direction. The pitch of propeller blades is designed for propulsion but is a compromise due to the variations in the wake field. This affects propulsive efficiency and cavitation behaviour.

Figure 33 is a wake field of 15-year-old 109,000 DWT tanker of low quality. The governing feature is a pair of vortices emanating from the bilges of the vessel indicated by the circular arrows. In larger parts of the wake field, the flow direction is now top down rather than bottom up as in Figure 32. BMS designed and delivered a Mewis duct for retrofit to this vessel. Associated calculations have been made by ibmv Maritime Innovationsgesellschaft mbH, Germany.

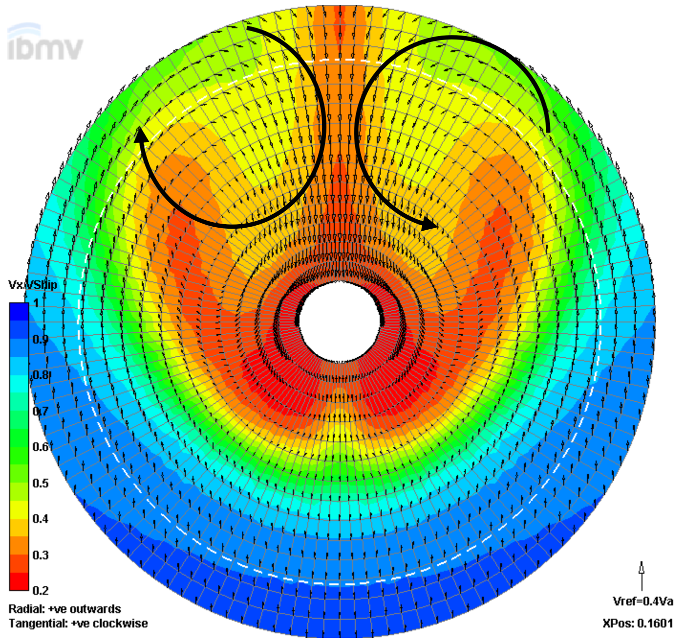


Figure 33. Wake field of low quality caused by vortices from the bilges of a 109,000 DWT tanker. Figure courtesy of BMS.

For the design of the duct, a special investigation was performed. A CFD (Computational fluid dynamics) calculation was made for a wake field in front of the propeller with the propeller operating with and without the duct (Figure 34). The wake field is dynamic as it changes with the position of the blades. Blue indicates the low-pressure fields (= accelerated axial flow) at three of the four blades. Although the wake field is less uniform with the duct, the overall inflow speed and in particular the tangential velocities are more homogenous. At the top, starboard position the flow is directed more to the port side with the duct, which represents a pre-swirl. Pre-swirl and improved homogeneity of the wake field lead to improved propulsive efficiency.

To illustrate the effect, the values of tangential velocity of the wake field without a duct have been subtracted from values with the duct (Figure 35). Here, the colour coding shows difference in tangential velocity, where blue means the tangential velocity clockwise increases due to the duct and red means tangential velocity counterclockwise increases. In the 12 to 3 o'clock positions, the flow is now faster in counterclockwise direction against the clockwise rotation of the propeller, which reduces the swirl in the wake of the propeller and therefore the losses. However, this does not necessarily mean a quieter propeller. Subjective observations of vibration and model test results regarding pressure fluctuations at blade rate harmonics did indicate improvements.

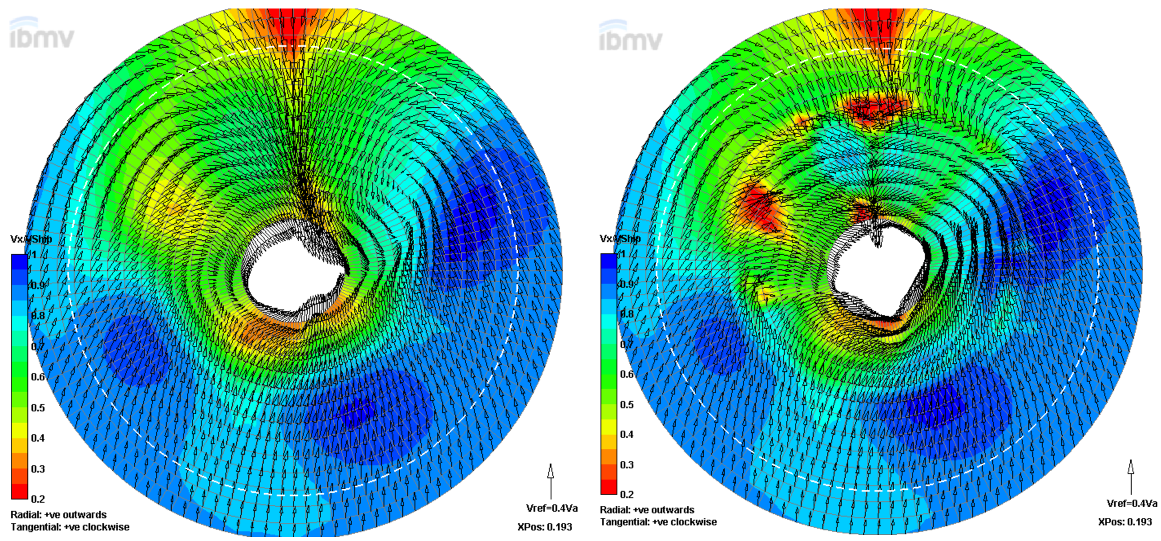


Figure 34. Wake field with operating propeller in front of propeller (left) without and (right) with Mewis duct.

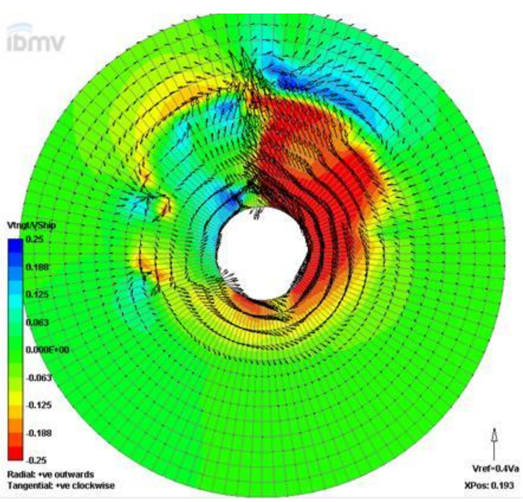


Figure 35. Difference of wake fields in Figure 34 for tangential velocity

The Mewis duct is an add-on device for retrofit. It is not typically a feature of a new design. One of the reasons of its remarkable economic success is also the situation that the propeller does not have to be changed to get improved results. Other WEDs lead to lighter running propellers, which then need to be changed to get the full benefit of the WED.

As the possibilities to optimize hulls are limited, there will always be a wake field that will look similar to Figure 32. It may be worth designing vessels from the start with such a duct and a propeller better adapted to the resulting wake field. Even if propulsive efficiency may not rise as it does in a retrofit situation, at least it might be expected that URN improves without sacrifice of propulsive efficiency.

A measurement of the effects of a WED on underwater radiated noise with a WED has not yet been performed.

6. Design Dilemmas

Striving to design and operate an efficient vessel should be the aim of all stakeholders in the shipping industry. Governments and environmental non-governmental organizations (NGOs) desire low CO_2 emissions, shipbuilders can deploy more advanced knowledge and technology, ship owners can demand a higher charter rate due to the lower fuel consumption and resulting reduced bunker costs of a vessel, and the vessel charterers can expect lower total costs (bunker costs + charter rate), resulting in a better price for freight owners to transport their goods. There is an expectation among stakeholders that measures to improve efficiency also have a positive effect on URN, so why are not all new vessels designed in a most efficient way?

The following are possible explanations for this phenomenon:

- In the vessel procurement process, from definition of the business case to delivery of the vessel, minimized fuel consumption is not the most important consideration. The currently inexpensive fuel prices do not motivate the value chain to invest in energy-saving technology.
- The dominant criteria for shipyard selection is low price of the vessel construction.

These immediate low-cost pressures result in vessels with minimized build costs by accepting inefficient designs that are easier to build. This increases the total life-cycle cost of the vessel; however, that is not an important consideration if the shipbuilder and financing company will not be the ones operating the vessels. Thus, many new vessels have considerable potential for optimization that would reduce the total life-time cost.

To start exploring the reasons behind this situation, we can assume that an “efficient” vessel shows the following features:

- Technical:
  - High capacity,
  - Low fuel consumption and low operating costs (repairs and lubricants) at a given speed,
  - Optimized operating condition (design condition matches actual operating condition), and
  - High reliability and low technical risks (maintenance of structure and systems, nautical accidents).
- Commercial:
  - Attractive (low) purchasing costs,
  - High resale value,
  - Easy and attractive financing, and
  - Low total costs of ownership.

In the design, building, and operation processes, the procedures in Table 7 can be applied to optimize vessel efficiency (Krüger and Pundt 2010), and can also expected to positively affect URN.

Table 7. Possible efficiency improvements during vessel design and operation (from an internal study at the Hamburg Ship Model Basin).

Procedure	Efficiency increase potential (%)
Optimize the hull form for minimized wave resistance	~5
Optimize hull form for continuous pressure distribution	~3
Optimize design and integrate results of model test to optimize hull-propeller-rudder interaction	~5
Optimize design and integrate results of model test to optimize wake field	~5
Design trim optimization	~3
Adapt design to a specific operation	~5
Sail the vessel in optimized trim	~3
Apply wake optimization devices	~5
Sail the vessel in favourable operating conditions	~7

These are examples and estimates-the efficiency optimization potential of a single feature itself, independent of other contributing factors, is very difficult to predict and even harder to verify in full scale. Executing several procedures will lead to a total efficiency improvement of less than the sum of the individual improvements. Depending on vessel type, we assume that a total efficiency increase of up to 25% can be achieved for an optimized design compared to a baseline 'low quality' version of the same type of vessel.

There are several reasons why these procedures are not applied, hard to influence, or process independent. A big challenge is the uneven distribution of technical knowledge throughout the international shipbuilding, shipping, and vessel financing industries. The holistic view of the whole vessel, its efficiency, and performance parameters are mostly found in ship model basins, as well as with selected vessel designers and advanced shipyards.

A major cause for unused optimization potential is the different interests of the charterers, owners, shipyards, and banks that are involved with constructing and operating a new vessel. In most cases, the organization that operates a vessel charters it from a vessel owner who is responsible for getting the vessel built. The owner is the interface to the shipyard and the bank that finances the construction. The charter/operator is rarely involved with the construction process. Figure 36 explores these relationships.

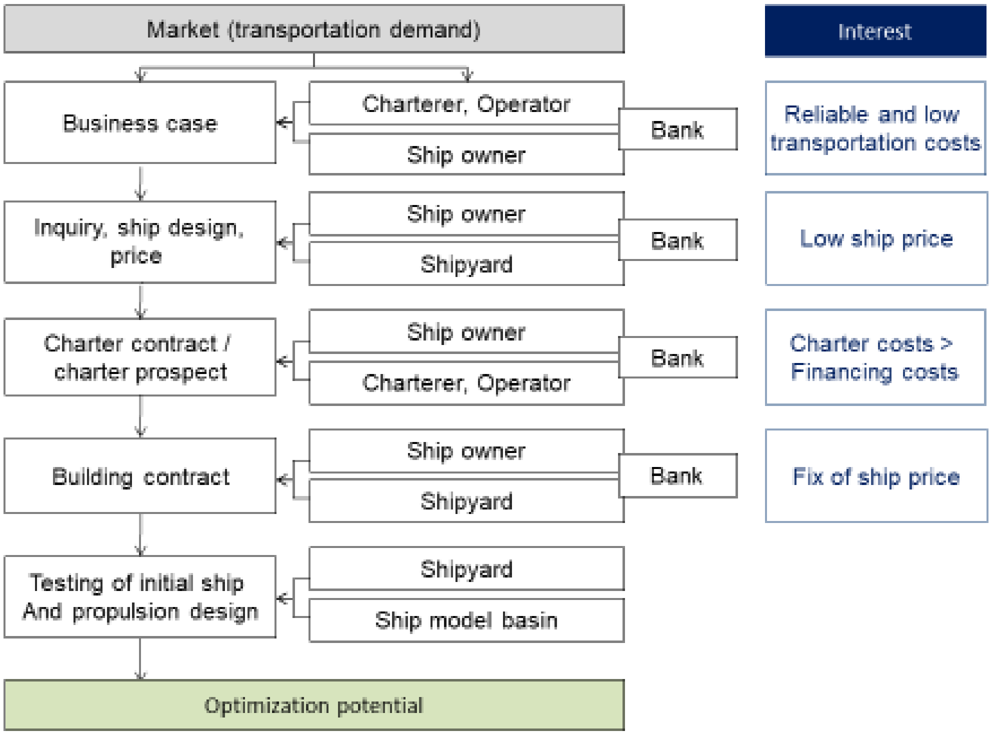


Figure 36. Typical stages for vessel design, construction, charter operation and the stakeholders involved.

Within this structure, the following processes lead to unused optimization potential:

- Charterers/operators are requesting vessels with predictable operating costs. Usually the level of technical expertise in vessel design is not institutionally incorporated in charter companies. Therefore, the expected fuel consumption (or efficiency) of the newly built vessel is derived from existing vessels of a similar class and with similar operating profile.
- Charterers and banks are usually risk averse. It is often more important to have a high cost prediction accuracy than potentially lower costs with higher risk margin.
- Based on market demand (charterers) and financial limitations (banks), shipowners define the performance parameters of a desired vessel. Shipyards will develop a design, which can meet these specifications with minimum costs and a resulting competitive price. Better performance or higher efficiency is not required by owners, as these will not benefit them.
- Shipyards have no ambitions to design or build a vessel exceeding the specification, as this will not benefit them.
- The tank test at a ship model basin is performed after the shipbuilding contract is signed and the price is set. The tank test may show substantial potential for efficiency optimization resulting in better than agreed fuel consumption. The resulting recommendations by the model basin may cover one or more items from Table 7. Most of these recommendations involve adapting the given design, may lead to increased building effort or increased building costs, or only in increased testing cost to be paid by the shipyard. But as the vessel price is already set, the shipyard would decline any increased effort without the prospect of additional compensation.
- Ship owners have no ambition to invest in any efficiency increase adaptions at this point of the contract, as reduced fuel consumption does not benefit them. Charterers are generally unaware of the test results and possibilities for efficiency improvement. For both charterers and banks, the issue is settled, and expectations fulfilled.

- Charterers, who are the only one benefitting from reduced fuel consumption, are generally not present when the model tests are performed, and improvement potential is discussed. A solution could otherwise be that charterers fund further model tests to optimize the vessel. However, this is not an accepted process. Note that in a large vessel, an improvement in fuel consumption by a few percent may save more than 1 million US dollars in a 5-year period.
- The improvement potential of a vessel during model tests is difficult to quantify. If the hydrodynamic experts expect an improvement by a particular change, they will be unable to guarantee success. Results may even reduce efficiency. However, experience shows that further optimization always leads to improvement, even if it is only 2%

External factors also contribute to unused optimization potential:

- The shipping and the shipbuilding sector have been in a continuous crisis since 2008. Price often defines the decisions made by shipyards or shipping companies. Several companies cannot consider long-term investments when their survival beyond two years is in jeopardy.
- Cargo vessel shipyards usually use their own designs and often develop them on past projects. This leads to conservative tendencies in the design and building process.
- Charterers and banks do often not employ personnel with the technical background necessary to understand all implications of an adapted and more efficient design. They need explanation suitable to their backgrounds and technical experts are often unable to explain their insights in a way that the lay-person understands. We can call this a "translation" problem. It is one of the major problems concerning this design dilemma.
- The improvement potential is laid out after all contracts are finalized when charterers/operators are not involved.
- There is limited transfer of efficiency-improving design knowledge or technology with Asian shipyards, which comprise a significant percentage of cargo shipbuilding capacity, but are often under government support or ownership.

These factors can also be considered in the context of reduction of URN levels. URN levels are not connected to a monetary consequence (yet) and thus are an even lower priority during the construction processes.

These factors should not give the impression that industry stakeholders are designing or building inefficient vessels on purpose. Shipyards and designers try to improve efficiency as best they can but within their limits of responsibility and possibilities. Better interaction between all stakeholders may lead to better exploitation of optimization potential.

7. Summary and Recommendations

This study was conducted by JASCO and DW-ShipConsult (DWSC) for Transport Canada to determine whether a vessel's underwater radiated noise (URN) level can be reduced without compromising efficiency. For this investigation, efficiency was quantified using the Energy Efficiency Design Index (EEDI). EEDI was introduced by the International Maritime Organization (IMO) as a tool to compel shipbuilders and owners to gradually improve the energy efficiency of the global fleet. URN is an underwater pollutant unlike any other in that it travels rapidly from its origin, but it ceases immediately when the source is removed—this is unlike chemical pollutants that spread slowly from their source and remain in the environment for decades after release. The most pervasive effect of URN from shipping on the environment is an increase in low-frequency sound levels that interferes with the ability of marine life to communicate and to use environmental queues for foraging and navigating.

Section 2 provided a summary of previous work to quantify the dependence of URN on vessel's design and operation parameters. Vessel speed through the water and actual draft were most correlated with URN, with faster vessels being louder and deep vessels being louder above 100 Hz. Design parameters were less correlated with URN than the speed and draft, and the significant parameters changed with vessel class. Overall, longer vessels were louder; most other size parameters are collinear with length and therefore could not be independently assessed. The voluntary vessel slowdown program in Haro Strait and Boundary Pass demonstrated that applying an 11-knot speed limit through sensitive areas reduced the average noise levels by 2 dB or more, and the short term sound levels by up to 12 dB. Thus, slower, smaller, and more lightly loaded vessels are associated with lower URN. This is at odds with trends in the shipping industry that are favouring larger and deeper vessels.

Section 3 introduces and calculates EEDI for the vessels considered in this study. The discussion showed that the best way to achieve a lower EEDI is to reduce the engine size and the design speed. Reducing speed is a design choice available to vessels that are currently optimized for higher speeds such as container ships; however, tankers and bulkers that already travel at slower speeds have few options available to easily achieve a lower EEDI. As discussed in Section 2, reducing speeds will reduce URN per vessel; however, if more vessels are needed to deliver the same amount of goods in the same time, then the net effect on URN is unclear. Similarly, a larger fleet may result in a net increase in greenhouse gas emissions. Alternately, the industry could switch to larger vessels; however, those tend to have higher noise emissions. The analysis of two versions of a new proposed Aframax tanker suggests that switching to an LNG main engine results in a ~20% reduction in GHG emissions which allows the tankers to meet their EEDI targets. This change will not affect the URN from the propellers; the effects on URN from the engines are unknown. The comparison of EEDI between the container ships and tankers indicates that container ships have more margin in their EEDI to accommodate changes to decrease URN that also decrease efficiency.

Section 4 is an analysis of the EEDI and URN for three tankers and five container ships. The vessels studied had EEDIs below the 2013 thresholds, and the container ships had EEDIs below the 2020 thresholds as well. No clear relationship between URN and EEDI was found. The variability in URN between vessels even of the same design was on the order of 6 dB, despite having similar drafts and speeds during the measurements.

Section 5 is a review of how the main source of URN from vessels is propeller cavitation and how it is affected by propeller design. Various options for increasing the cavitation inception speed are presented. The effects of propeller improvements on URN from the large-scale adoption of higher inception speed propellers is difficult to predict. Measurements conducted from test designs indicate that once the propeller is cavitating the energy in higher frequency bands is increased by a similar amount to the reduction in the fundamental energy. As the propeller becomes more optimized for high cavitation inception, its efficiency declines, so that there is an inherent trade-off between efficiency and URN reduction through propeller design. The effects of a smooth wake field are also reviewed. Wake equalizing devices are known to increase the efficiency of vessels; however, no measurement of URN before and after modification has been performed.

As a rule of thumb, cavitation increases with propulsive efficiency, at least to the point where vibrations inside the vessel exceed the allowed limits by the Classification Societies. Thus, the improvements in underwater noise we are seeing from slower vessels is due in part to older vessels reducing their speeds without optimizing their propellers. An optimized propeller for these vessels would likely increase their URN again.

Finally, in Section 6 the structure of the ship building, financing, ownership, and chartering business is summarized. It presents estimates of the maximum efficiency improvements that can be obtained by good design and optimized operations of a vessel. Most efficiency improvements must be applied at design time. The primary efficiency improvements during operations are associated with running the vessel at its design depth and speed. Because the builders, owners, and financiers are generally separated from the long-term operational costs of running vessels, there is limited incentive to build more efficient vessels. This reality was one of the motivations behind the IMO developing and mandating the EEDI. Reductions in URN are even more difficult to bring to the attention of builders and owners, as there are almost no financial incentives for reducing noise. All three of the ship owners that provided data on their vessels in our study are exceptions to this rule. They own and charter their vessels and hence are interested in their efficiency; they are also invested in their communities and appreciate that the value of minimizing noise is not financial.

From this study we conclude that to date the primary result of EEDI is a reduction in the average vessel speed, i.e., slow steaming that reduces the greenhouse gas emissions of individual vessels. The net effect of this change on the total emissions is unclear and requires further investigation. Achieving improved EEDI does not improve URN, except in the context of reduced operational speed, which may not be substantial if the vessels employ propellers optimized for efficiency at the reduced speed. Again, the net effects of reduced speed on total noise emissions is unclear if more or larger vessels are the solution. The results from the Haro Strait and Boundary Pass measurements indicate that reducing the speed of vessels optimized for efficiency at higher speeds does reduce URN over large areas.

An important lesson learned from this project is that affecting the operational efficiency of vessels will be essential to motivate ship builders and financiers to invest in better designs. We must also consider the cumulative noise and GHG efficiency of the global fleet rather than just individual vessels when implementing measures to improve efficiency. With these lessons in mind, we recommend several follow-on studies:

a. Conduct a basin scale modelling study to examine the trade-offs between more slow, large vessels and fewer, but smaller and faster vessels.

b. Conduct a similar study to this one where we examine the relationship between EEOI and URN.

c. Look for an opportunity to quantify the URN of a vessel before and after fitting a WED. Ideally multiple measurements of the vessel would be made in both states to reduce the variability inherent in vessel source level measurements.

d. Look for an opportunity to quantify the URN of vessel(s) that have switched to slow steaming before and after fitting an optimized propeller. Ideally multiple measurements of the vessel would be made in both states to reduce the variability inherent in vessel source level measurements.

e. Conduct an analysis of the VFPA URN data set to determine if there is a difference in noise profiles for vessels with LNG propulsion compared to those using diesel.

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Appendix A. Additional Spectrograms

This appendix contains spectrogram for the vessels not shown in Section 4.

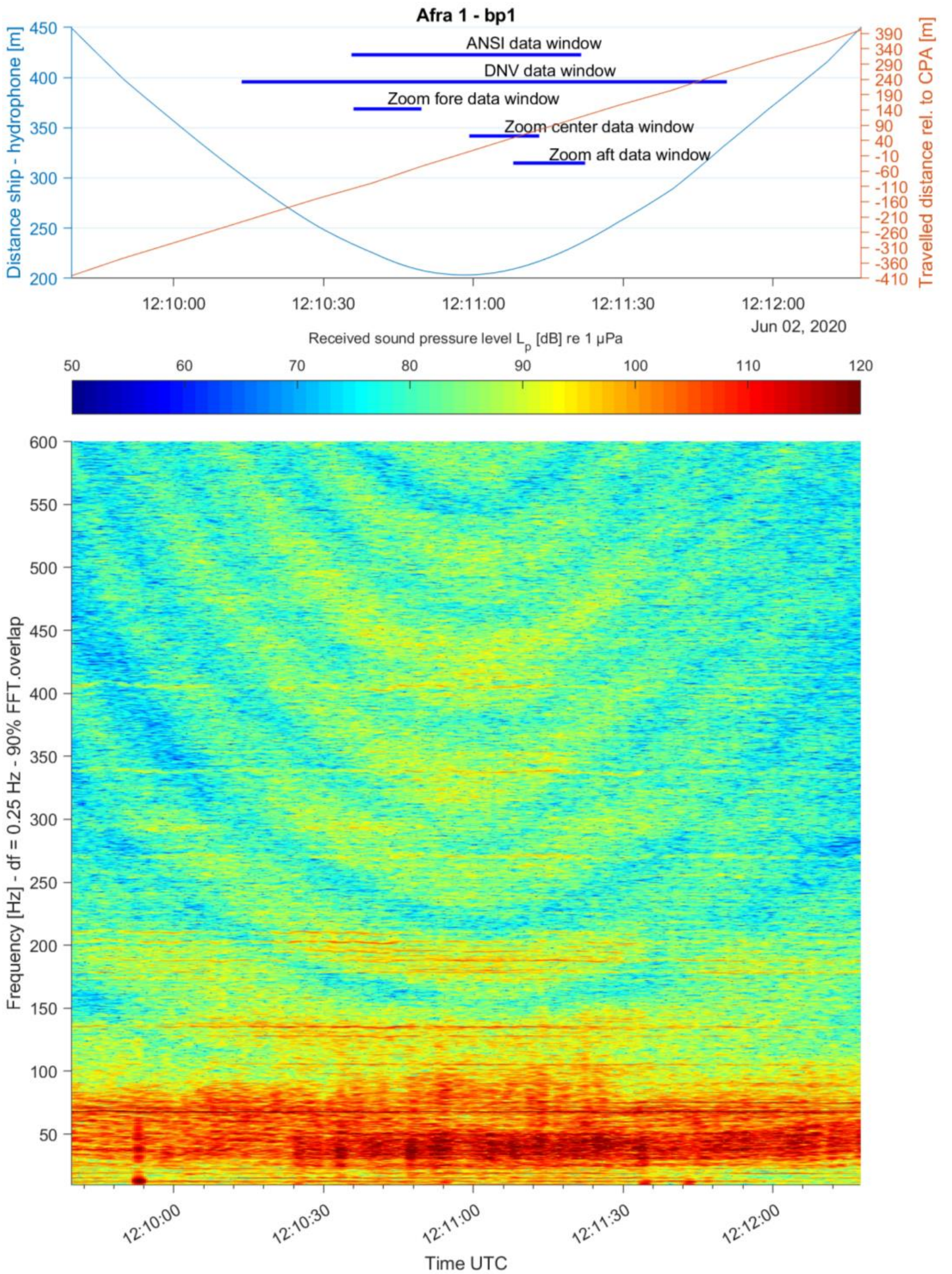

Figure A-1. Spectrogram analysis for identification of dominant noise sources of Afra 1.

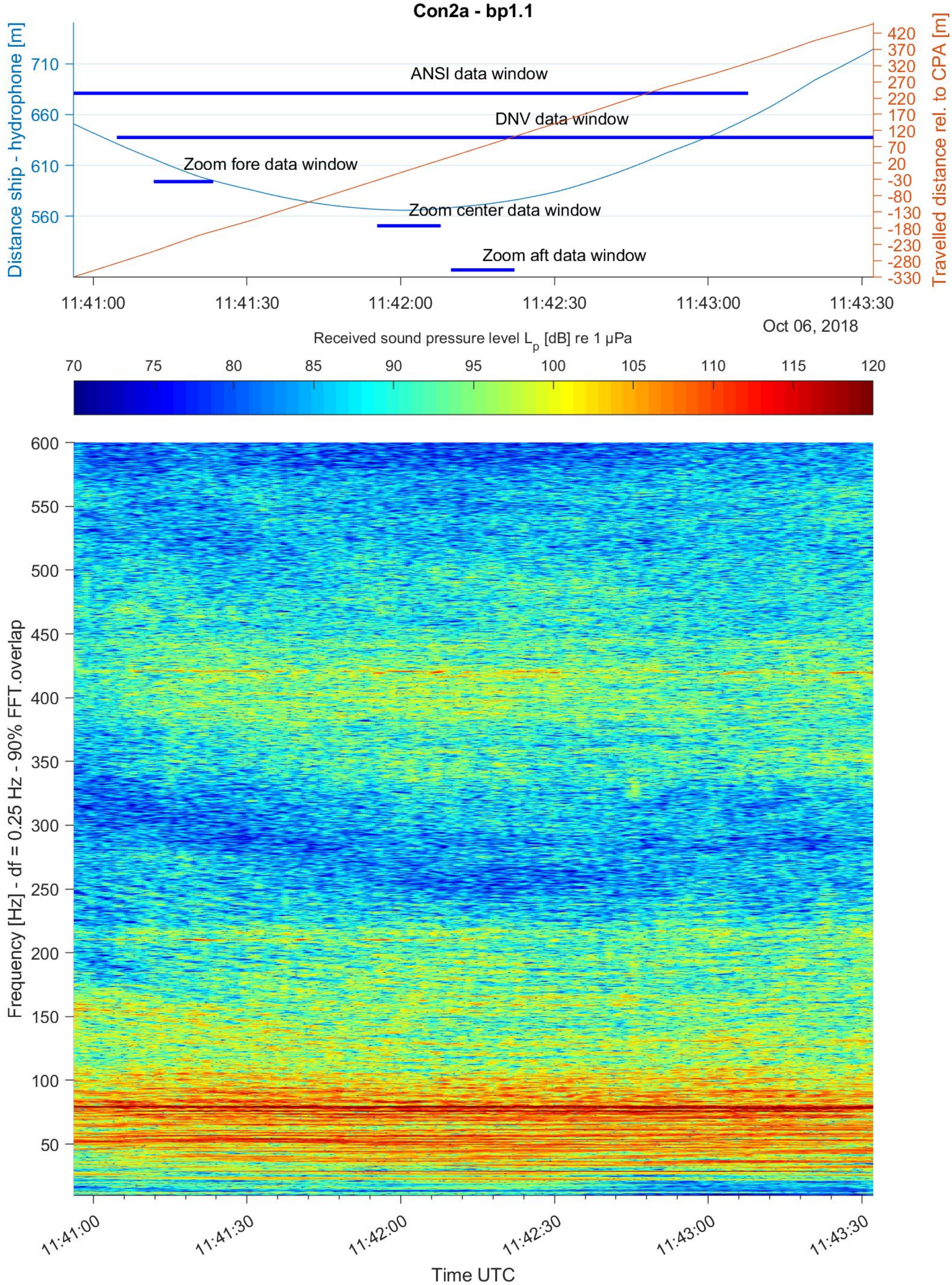

Figure A-2. Spectrogram analysis for identification of dominant noise sources of Con 2a.

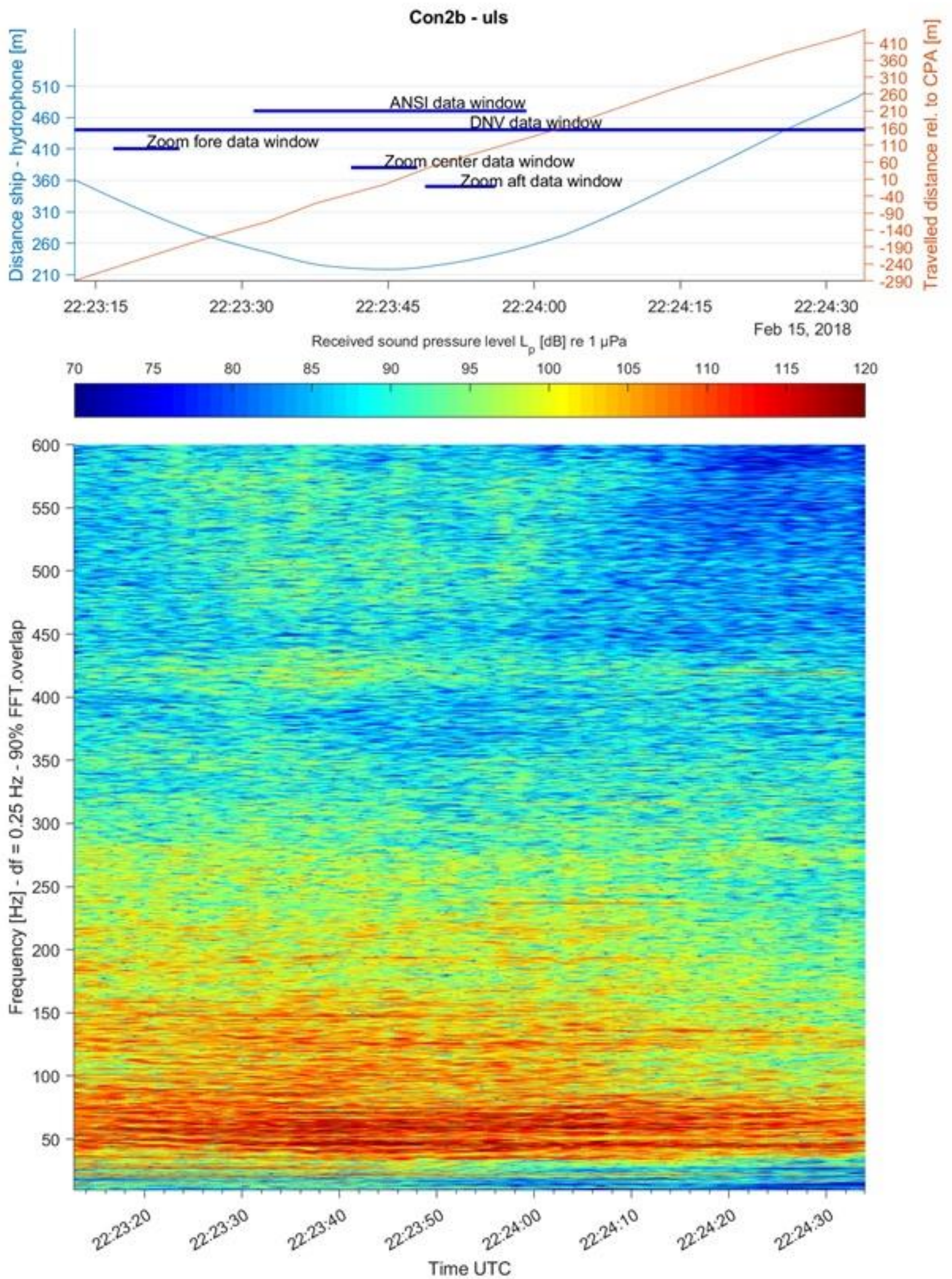

Figure A-3. Spectrogram analysis for identification of dominant noise sources of Con 2b.

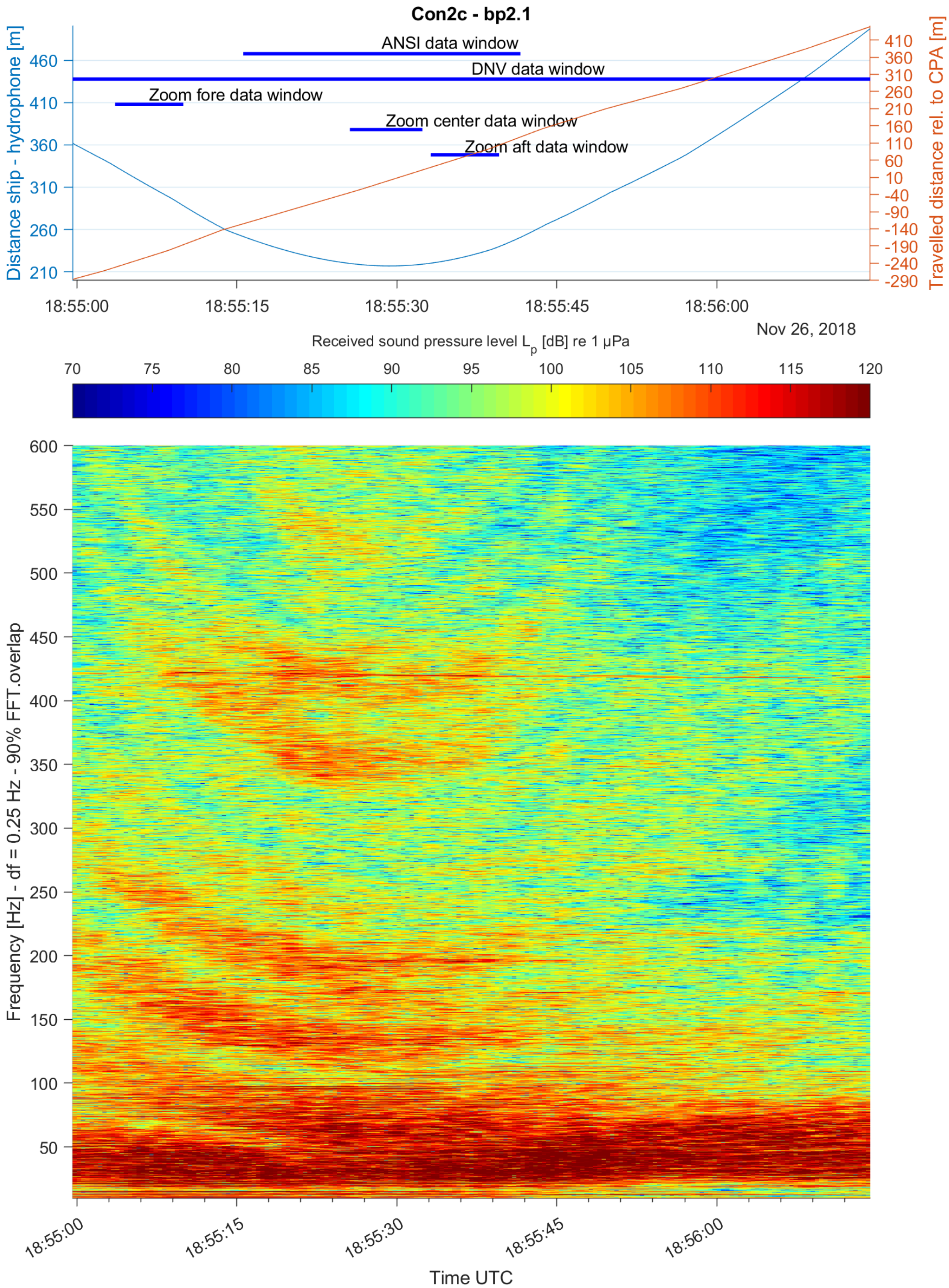

Figure A-4. Spectrogram analysis for identification of dominant noise sources of Con 2c.

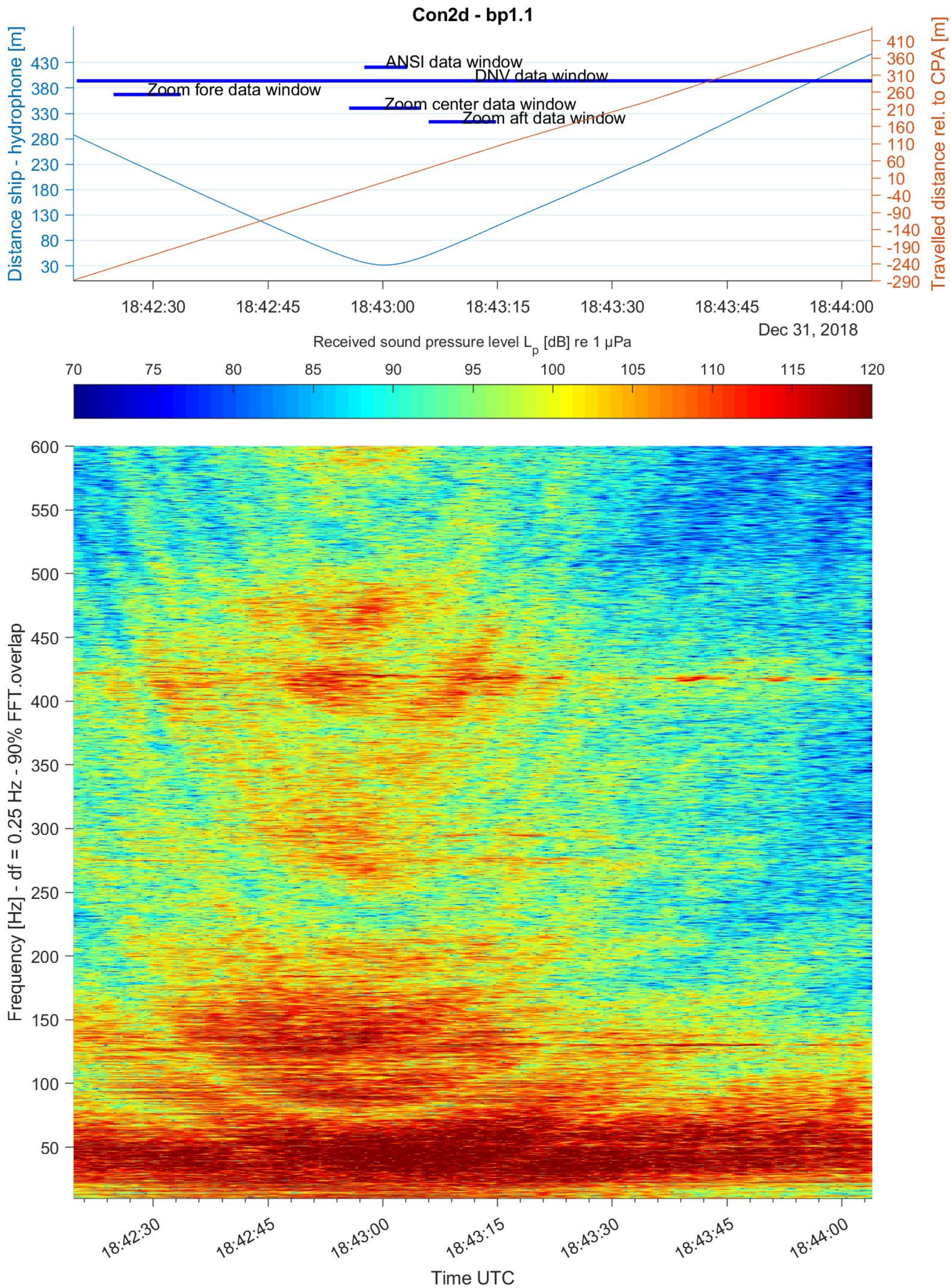

Figure A-5. Spectrogram analysis for identification of dominant noise sources of Con 2d.