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Modeling of ships as a source of underwater noise

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Abstract

In this paper, a methodology is presented for modeling underwater noise emissions from ships based on realistic vessel activity in the Baltic Sea area. This paper combines the Wittekind noise source model with the Ship Traffic Emission Assessment Model (STEAM) in order to produce regular updates for underwater noise from ships. This approach allows the construction of noise source maps, but requires parameters which are not commonly available from commercial ship technical databases. For this reason, alternative methods to fill in the required information were necessary. Most of the parameters needed contain information which are available during the STEAM model runs, but features describing propeller cavitation are not easily recovered for the world fleet. Baltic Sea ship activity data was used to generate noise source maps for commercial shipping. Containerships were identified as the most significant source of underwater noise, with a significant potential for increasing contribution to future noise emissions.

1. Introduction

It is recognized that anthropogenic noise might have adverse effects on the marine environment. Scientific results unequivocally suggest that animals react to sound and sometimes with devastating results (Rolland et al., 2012; Yang et al., 2008), but more commonly give rise to strong avoidance reactions (Moore et al., 2012). Not all marine life is sensitive to the same kind of noise; low frequency shipping noise (<1000 Hz) may be relevant for several fish species, whereas this range may be less relevant for marine mammals which can hear sounds up to 200 kilohertz (Nedwell et al., 2004). The problem of underwater noise was recognized by the European Commission (EC), which included sound as the eleventh descriptor in the Marine Strategy Framework Directive (MSFD) and made it analogous to pollution (European Parliament and Council of the European Union, 2008). Global maps of shipping activity help to understand that the omnipresence of waterborne traffic will contribute to noise levels of all sea marine areas. The levels of underwater sound have been increasing since the advent of steam-driven ships (Hildebrand, 2004, 2009), but shipping is only one source of underwater noise and both natural and anthropogenic sources contribute to noise levels.

The primary source of underwater noise from ships is the propeller cavitation. Cavitation occurs when a fast rotating propeller pushes water with its blades and vacuum forms on the backside of the blade. Water boils and it forms collapsing bubbles which violently burst, emitting noise in the process. All propellers cavitate when rotated fast enough, but propeller design can affect how easily this occurs. The downside is that efficient propulsion and suppression of cavitation are two conflicting requirements (Carlton, 2010). Currently there exists design rules (IMO, 2014) for energy efficiency of new ships, but no binding regulation to mitigate underwater noise from ships (IMO, 2012). With this setup, it is easy to understand that designing an efficient propeller is more important than designing a silent propeller, unless low noise signature is required on the battlefield(warships), or not to disturb test subjects (research vessels) (Leaper et al., 2014).

Modeling underwater noise from ships has been done for a long time and various models have been designed to describe noise sources based on measurements done since the World War II. However, these models often rely on confidential data sets, which are not necessarily available for civilian research efforts, but during the last two decades significant effort has been made to generate an experimental basis for noise model development (Arveson and Vendittis, 2000; Kipple, 2002; McKenna et al., 2012; Wales and Heitmeyer, 2002). These data have been used to construct noise source models, which rely on parametric description of ensemble source spectra for merchant vessels. Recently, Wittekind (2014) described the noise sources using a method which describes ships as individual sources of noise which arise from individual technical features and vessel operation.

Automatic Identification System (AIS) data have been used to track exhaust emissions from ship traffic, but its use in underwater noise source modeling has been a subject of few studies where it has mostly been used to locate the noise sources relative to hydrophone setups (Hatch et al., 2008; McKenna et al., 2012). Our study carries this idea forward and builds on the development of the Ship Traffic Emission Assessment Model (STEAM) of Jalkanen et al (Jalkanen et al., 2009, 2012, Johansson et al., 2013, 2017). This approach combines the vessel level technical description, an existing noise source model (Wittekind, 2014) and ship activity obtained from AIS data, as well as facilitates the regular updates of noise source maps of any level, ranging from local to global, depending on the availability of AIS data. These data could be used to assess shipping noise, further the understanding of noise as an environmental stressor and provide tools for future sustainable governance of the sea areas.

The aim of this paper is to a) introduce a methodology for noise source mapping, which could be used for routine annual reporting of underwater noise emissions, b) provide insight on the geographical distribution of vessel noise in the Baltic Sea area and c) provide a summary of results for noise emissions from Baltic Sea shipping during year 2015.

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2. Materials and methods

2.1. Ship Traffic Emission Assessment Model

The Ship Traffic Emission Assessment Model (STEAM) of Jalkanen et al (Jalkanen et al., 2009, 2012, Johansson et al., 2013, 2017) was used in this study. The Wittekind noise source model (Wittekind, 2014) was built into STEAM which facilitated noise source description based on technical characteristics of individual vessels. The activity data used for this study consisted of 500 million AIS position reports sent by the ships sailing the Baltic Sea during year 2015. The data were provided by the member states of the Helsinki Commission (HELCOM). STEAM uses AIS to describe vessel location, time, identity and speed over ground and combines it with vessel technical data of IHS Fairplay (IHS_Global, 2016) and publicly available shipping data sources (classification societies, engine manufacturers). This combination allows for predictions of instantaneous engine power, fuel consumption and emissions as a function of vessel speed, further details of the model can be found in a recent paper of Johansson et al (2017).

2.2. Wittekind noise source model

Wittekind noise source model describes the ship noise as a combination of three contributions, which arise from low and high frequency cavitation and machinery noise. The cavitation contributions are dependent on vessel speed whereas the machinery part is not. This has important implications in noise source map generation and the time integration part of this work, which will be described in Section 2.6. The three components are described by Wittekind as

$$SL(f_k) = 10log_{10}\left(10^{SL1(f_k)/10} + 10^{SL2(f_k)/10} + 10^{SL3(f_k)/10}\right) \quad (1)$$

In (1) f_k is the center frequency of the k^{th} frequency band. The SL1 (Eq (2)) represents the low-frequency cavitation noise, the second contribution (SL2; (3)) describes the high frequency cavitation and the third (SL3; Eq (4)) represents the machinery noise. In the Wittekind model, the low and high frequency cavitation (SL1 and SL2) were obtained from fitting to experimental data (Arveson and Vendittis, 2000) and the rest (SL3) from their own measurements and observations:

$$SL1(f_k) = \sum_{n=0}^{5} c_n f^n + 80log_{10}\left(\frac{4C_B V}{V_{cis}}\right) + \frac{20}{3}log_{10}\frac{\nabla}{\nabla_{Ref}} \quad (2)$$

$$SL2(f_k) = -5\,ln\,f - \frac{1000}{f} + 10 + \frac{20}{3}log_{10}\frac{\nabla}{\nabla_{Ref}} + 60log_{10}\frac{1000C_B V}{V_{cis}} \quad (3)$$

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$$SL3(f_k) = 10^{-7}f - 0.01f + 140 + 15log_{10}m + 10log_{10}n + E \quad (4)$$

In Eq (2), the f denotes the center frequency of the kth octave band, the other constants are c_0=125, c_1=0.35, c_2=-8E-3, c_3=6E-5, c_4=-2E-7, c_5=2.2E-10 and C_B denote the Block coefficient, V indicates the instantaneous vessel speed obtained from AIS, V_{cis} represents the cavitation inception speed (see Section 2.5 for a more detailed discussion of V_{cis}), ∇ is the vessel displacement and ∇_{Ref} the reference vessel displacement, for which 10 000 tons should be used. In Eq (4), parameters m and n represent the mass (in tons) and number of operating main engines, whereas E is the engine mounting parameter which indicates whether the engine is resiliently (E=0) or rigidly (E=2) mounted.

As can be seen, the Wittekind model uses parameters which are ship specific and will lead to individual noise source description depending on vessel features, but some of these are not available from ship databases which provide other vessel specifications. However, there are numerous parameters which need to be derived during the noise source calculations. Some of these, like c_B, ∇, n are already calculated during a regular STEAM run, but cavitation inception speed (V_{CIS}), engine mass (m) and mounting parameter (E) were determined in the following manner.

2.3. Main engine mass

Main engine mass is not routinely included in commercial ship databases and we have augmented the STEAM database with engine masses obtained from technical documentation of engine manufacturers and engine catalogues (Barnes et al., 2005). Engine mass could be determined explicitly for about two thirds of the global fleet. For the remaining cases, a linear function Figure 1) was developed to estimate engine mass based on the size (installed power) of engines. For four-stroke engines, main engine mass is determined by multiplying the installed kW/engine with 0.0155 which corresponds to 65 kW/ton power/mass ratio and falls between the range of values proposed by Watson (Watson, 1998). Cylinder arrangement (in-line vs V arrangement) has an impact on predicted mass, because in-line engines tend to be heavier than V engines which leads to lower power/mass correlation than in case of two stroke engines (Figure 2). This does not apply to 2-stroke engines, because all two stroke engines the cylinder arrangement is of in-line type.

There are about 19 600 vessels equipped with four stroke engines, mass of which needs to be evaluated with the proposed power/mass methodology. The quality of linear fit is slightly worse for four stroke engines (R^2=0.814) than for two stroke engines (R^2=0.955) because of variable cylinder arrangement described above. There are 24 300 vessels with two-stroke engines the mass of which can be determined from manufacturer documentation. Mass of two-stroke main engines for 5500 ships need to be estimated based on installed engine power (in kW). Further, there are 3100 vessels for which engine stroke type is unknown. In unknown cases, most similar vessel details (Johansson et al., 2017) are used to determine missing technical data.

For two-stroke engines, engine power output is multiplied with 0.0322 (red line). For example, Man B&W 10K98MC-C engine, the predicted mass is 1725-1797 tonnes, whereas manufacturer specifications indicate mass of 1854 tonnes. Watson

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recommends 0.035-0.045 tons/kW (upper and lower black lines of Figure 2). It should be noted, that the range recommended by Watson (Watson, 1998) leads to higher engine masses than the best fit to engine setup of the current fleet of 24 300 samples. For turbine machinery, 0.001 ton/kW should be used according to Watson. There are 480 entries in the ship database, which indicate the use of turbine machinery, either gas or steam versions. The accuracy of mass predictions for vessels equipped with turbine machinery is poor. No correlation was found between engine mass and power output. The Watson recommendation was adopted and 0.001 ton/kW was used for all turbine machinery. It should be noted that the applicability of the Wittekind noise source model to turbine machinery is an extrapolation of original results and are likely to result in large uncertainties.

2.4. Engine mounting

Unfortunately, engine mounting parameter is not available in the available technical databases. Main engines of a ship can be bolted directly to the rigid box girder without additional damping material to absorb vibrations of engines. This is known as rigid mounting and it is usually applied to large two-stroke engines. Resilient mounting of the engine is used if it is necessary to reduce structure-borne vibrations or noise which would otherwise be transmitted to the hull. According to Rowen (2003), resilient mounting is usually applied to medium and high speed diesels, which are sufficiently rigid in bending and torsion. In this work, all two stroke engines have been assigned “rigid mounting” status and “resilient mounting” is assumed for all four stroke engines.

2.5. Cavitation inception speed

The description of cavitation is, among other factors, a function of propeller disc area and propeller tip speed. Commercial ship databases do not contain enough information, like the number of blades and diameter of propellers installed in ships, necessitating an alternative approach to generate the cavitation inception speed. An alternative method to determine this parameter was developed based on discussions with a manufacturers of propulsion equipment. Based on these discussions, an approach based on vessel Block coefficient and design speed was developed (5).

$$V_{CIS} = min\{max[(1.42 - 1.2c_B) * V_d; 9]; 14\} \tag{5}$$

where V_{CIS} is the cavitation inception speed (knots), C_B is the Block coefficient and V_d the design speed of the vessel (knots). Between 9 and 14 knots the cavitation inception speed is a linear function of the Block coefficient (hull shape). According to Eq (5), all ships will cavitate at 14 knots; especially the fast RoPax, cruise ships and most modern containerships will fall into this end of the range. This is in contrast to most bulk cargo carriers and tankers for which V_{CIS} is close to nine knots. With these extremes, there are various exceptions, for example very large containerships (over 18 000 TEU capacity) and new LNG

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carriers which perform less well and have lower inception speed than most of the ships of their type. It is unclear why this occurs, but highly efficient propellers may not be the most silent ones.

2.6. Noise source map generation

In order to represent underwater noise emissions as a map, an approach was developed to facilitate this form of emission reporting. The source level is related to the power emitted (P_k) in frequency band k, as:

$$SL_k[dB\ re\ 1\ m, 1\ \mu Pa] = 10 log_{10} \frac{P_k}{P_{Ref}} \quad (6)$$

where $P_{Ref} = \frac{2\pi p_{ref}^2}{\rho c}$ is a reference power, ρ and c are density and speed of sound while p_{ref}=1 μPa. Assuming that all noise sources are uncorrelated, the total emitted power from all M ships in area A at time t is given as:

$$P_k^{tot}(t) = \sum_{m=1}^{M} P_{k,m}(t) \quad (7)$$

where $P_{k,m}(t)$ is the sound power (in J s^{-1}) emitted by ship m. This quantity is additive and facilitates the summation of ship specific noise energy over a specific time period (in Joules). The sound power map is more of a visual aid than a direct input dataset for noise propagation modeling, which may prefer point source description of noise sources (Karasalo et al., 2017). Presenting sound energy as geographically distributed quantity will help visualizing noisy areas. Similar to the emission maps of atmospheric pollutants, noise source maps should not be taken as a representative description of underwater noise any more than an emission map of NO_x does not describe airborne pollutant concentrations. The maps presented in this work describe the noise sources, not underwater propagation of noise.

Ships spend a significant part of their activity in harbor areas (Smith et al., 2014). The time integration step (Eq (7)) leads to a situation where harbor areas were represented as significant sources of underwater noise. This is a feature of the machinery contribution of noise source description (see Eq (4)) which remains non-zero when ships are standing still. With the current approach it is not possible to distinguish between ships standing still with engines on or off. The Wittekind noise source model is intended for moving vessels and application of this model to stationary vessels would have been a clear extrapolation of the original intention. For that reason, we chose to only apply the time integration of sound power for moving ships. In STEAM, time integration of sound power is applied only for cruising and manoeuvring modes of vessel operation and stationary vessels do not contribute to total sound energy regardless of the fact that there may be auxiliary engines running during harbor visits which may contribute to the emitted underwater noise. Noise from auxiliary engines is not modeled in this approach even if they may be a significant source of atmospheric noise in harbor areas.

3. Results and discussion

3.1. Shipping noise emissions in the Baltic Sea area

The noise maps were generated for third octave bands which have 63 (56.2-70.8 Hz), 125 (112-141 Hz) and 2000 (1780-2240 Hz) Hz central frequencies (Van der Graaf et al, 2012). The two lowest bands are relevant to various fish species whereas the 2 kHz band is relevant for marine mammals (Nedwell et al., 2004; Nikopouloulos et al, 2016). Using the methodology described above, the generated noise source maps for Baltic Sea shipping in 2015 (for 125 Hz band) are depicted in Figure 3.

As can be seen from Figure 3 noise source maps have noise hotspots on the main shipping lane in the Danish Straits, between islands Fyn and Sjælland. Also, outside Kiel and Rostock harbors high values for sound energy were predicted. The annual noise energy emitted in the 125 Hz band was 58 gigajoules during 2015 and highest contributions were from cargo and container ships as well as tankers. Containerships alone represent about three percent of ships in the Baltic Sea during 2015, but they are responsible for 25% of noise energy (Figure 4; Table 1).

For most cargo ships V_{CIS} is predicted to be close to nine knots, with the exception of containerships, and about one quarter of these slow vessels sailed in 2015 slower than their predicted cavitation inception speed (Figure 5). If the cargo carrying fleet in the Baltic Sea area returns to normal operation with speeds closer to their design speed, it is very likely that a significant increase in noise energy will be seen for the quarter of the cargo fleet now operating at slower speeds than their V_{CIS}. This increase could happen without increasing the fleet size at all. A significant portion of oil product tankers and cruise vessels were operating with speeds lower than their cavitation inception speed. It may very well be that the contribution from oil tanker fleet may increase when the slow operating vessels speed up again, but their overall contribution to sound power is quite low, only about two percent. However, if all of the twenty percent of containerships which in 2015 operated under their V_{CIS} speed up, the impact on sound energy increase will be significant, because containership contribution to overall sound power is high.

3.2. Uncertainty evaluation

Karasalo et al (2017) tested the performance of the Wittekind noise source model with inverse modeling to hydrophone measurements. The transmission loss of the measured noise signature was modeled using XFEM code (Karasalo, 1994) to obtain the noise source at reference distance. In their paper, Karasalo et al (2017) observed a good fit between the Wittekind predictions and observed signals for cargo ships and tankers and tugboats, but larger differences were observed with passenger and RoRo vessels for which the Wittekind model overestimated the noise source levels. It is very likely that this is because the Wittekind model was mainly intended for large ocean-going vessels with a single fixed pitch propeller or a single controllable pitch propeller when they are operated close to their design pitch (Wittekind D, Oct 2017, personal communication).

Voluntary operation of a vessel with lower speed (slow steaming) may work as a noise mitigation option for deep ocean vessels with a single fixed pitch propeller, but it may not work with ships equipped with controllable pitch (CP) propellers and it may lead to higher than expected noise emissions (Li, D-Q & Hallander, 2015).

Significant uncertainty may be involved in the estimation of the cavitation inception speed (V_{CIS}), which is not readily available from any of the ship databases directly and was estimated using the vessel design speed and hull form (see Eq. 5). Contribution of V_{CIS} to vessel noise source level is significant, because at speeds below this threshold value vessel noise is notably lower than above it. This uncertainty can be reduced with more in-depth research on cavitation inception. These experimental findings should be released as open access reports and datasets to facilitate further research on underwater noise emissions. In case of controllable pitch (CP) propellers the speed of the vessel is regulated with the propeller pitch and not necessarily adjusting the rotational speed of the propeller. Without additional information about marine propellers used in ships it is difficult to assess the details of cavitation. Modern passenger vessels are usually equipped with multiple four-stroke engines and have more than one propeller, often CP type. In 2015, about ten percent of the vessels sailing the Baltic Sea were equipped with two or more propellers and the contribution of these ship types to the total noise energy in 125 Hz frequency band was around 13%. It is likely that the accuracy of noise emission of the passenger vessel fleet is worse than that of the cargo ships, but this will not change the main conclusions of this paper.

The Wittekind model does not include contributions from auxiliary engines, which may be a significant noise source in port areas. This was one of the reasons this contribution has been exempted from time integration of sound power. Neglecting the continuous time integration during harbor visits will also produce some uncertainty to final results, but the magnitude of this contribution is difficult to estimate because the current approach will not be able to distinguish between ships anchored with their engines shut down and ships which keep their engines running even when vessels remain still. It is very likely that harbor areas are not significant fish or marine mammal habitats, which should reduce the significance of this uncertainty for noise impact assessments on marine life.

4. Summary

Underwater noise is rarely a design parameter for new ships, unless warships or research vessels are considered, and only voluntary guidelines to mitigate vessel noise exist. Currently, for the commercial fleet, efficiency of the propeller is more important than low noise emissions and these two conflicting requirements may lead to worse noise problems when more energy efficient designs are required. Cavitation of propellers is avoided to alleviate mechanical problems arising from erosion, not to mitigate noise emissions.

Our conclusions concerning this work are the following. We have presented methodology how underwater noise emissions can be derived from ship activity and technical data. This methodology facilitates annual updates of noise source maps for frequency bands of 63, 125 and 2000 Hz regardless of the study scale. In principle, other frequency bands could also be reported, the methodology presented enables it, but the bands chosen for this work represent those considered relevant for marine life. With global AIS data, also global noise source studies are possible. Modeling work can also provide an estimate of noise source development over the years for which AIS data is available. For the Baltic Sea during 2015, the most significant noise source are the bulk carriers and containerships. Container vessels represent about three percent of the total number of

IMO registered vessels but are responsible for one quarter of noise power emitted. Also, it was discovered that about twenty percent of the containerships currently operate on speeds below the cavitation inception speed. If these vessels increase their operating speed closer to their design speed it is very likely that a significant increase of underwater noise may occur in the Baltic Sea area without increasing the fleet size at all.

It is unclear what kind of physical impact the current level of shipping noise has on marine life in the Baltic Sea area. Shipping is only one source of underwater noise and many other sources exist, both natural and anthropogenic. Noise is not routinely monitored, but it is done in many research projects concentrating on underwater noise. However, there are no long-term observations of noise which could be used to determine how noise levels have developed in the Baltic Sea in the past years. Our hope is that this work could be used to estimate the noise levels based on observed vessel activity and modeling tools. It is evident that routine monitoring is required. In general, modeling must rely on robust experimental data, which should be available to assess the performance of the modeling work. Currently, only limited opportunities to do this exist from a handful of research projects, but national measurement networks and international cooperation is called for. The noise source emission maps are available in SHEBA project data portal (http://sheba.hzg.de/thredds/catalog.html).

Author contributions

JPJ was responsible for overall coordination of the work and the Wittekind noise model adaptation for STEAM. LJ was responsible for technical implementation of the noise module and running the STEAM model. ML and RB provided technical expertise in noise model selection and adaptation. PS, MÖ, IK, MA were responsible for developing a methodology for noise source mapping and consecutive noise propagation modelling, which contributed to the uncertainty evaluation. HP and JP provided expertise on relevant impacts on marine life and contributed to noise source mapping method development.

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References

Arveson, P. T. and Vendittis, D. J.: Radiated noise characteristics of a modern cargo ship, J. Acoust. Soc. Am., 107(1), 118–129, doi:10.1121/1.428344, 2000.

Barnes, J., Langdon, M., Tolley, K., Wall, L. and Skelton, M.: Marine Engines 2005 - Motorship Supplement, Motorship, 2005.

Carlton, J.: Marine Propellers and Propulsion, Third Edit., Elsevier Ltd, Oxford, UK., 2010.

European Parliament and Council of the European Union: Directive 2008/56/EC of the European Parliament and of the Council, Off. J. Eur. Union, 164, 19–40, doi:10.1016/j.biocon.2008.10.006, 2008.

Van der Graaf AJ, Ainslie MA, André M, Brensing K, Dalen J, Dekeling RPA, R. S. and Tasker ML, Thomsen F, W. S.: European Marine Strategy Framework Directive - Good Environmental Status (MSFD GES): Report of the Technical Subgroup on Underwater noise and other forms of energy. [online] Available from: http://ec.europa.eu/environment/marine/pdf/MSFD_reportTSG_Noise.pdf, 2012.

Hatch, L., Clark, C., Merrick, R., Van Parijs, S., Ponirakis, D., Schwehr, K., Thompson, M. and Wiley, D.: Characterizing the relative contributions of large vessels to total ocean noise fields: A case study using the Gerry E. studds stellwagen bank national marine sanctuary, Environ. Manage., 42(5), 735–752, doi:10.1007/s00267-008-9169-4, 2008.

Hildebrand, J.: Sources of Anthropogenic Sound in the Marine Environment, Rep. to Policy Sound Mar. Mamm. An Int. Work. US Mar. Mammal Comm. Jt. Nat. Conserv. Comm. UK London Engl., 50(2), 1–16, doi:10.1016/j.marpolbul.2004.11.041, 2004.

Hildebrand, J. A.: Anthropogenic and natural sources of ambient noise in the ocean, Mar. Ecol. Prog. Ser., 395, 5–20, doi:10.3354/meps08353, 2009.

IHS_Global: SeaWeb database of the global ship fleet, 2016.

IMO: 2014 GUIDELINES ON THE METHOD OF CALCULATION OF THE ATTAINED ENERGY EFFICIENCY DESIGN INDEX (EEDI) FOR NEW SHIPS, MEPC 66/21/Add.1., 2014.

IMO SUB-COMMITTEE ON SHIP DESIGN AND EQUIPMENT: PROVISIONS FOR REDUCTION OF NOISE FROM COMMERCIAL SHIPPING AND ITS ADVERSE IMPACTS ON MARINE LIFE, DE 57/17., 2012.

Jalkanen, J. P., Brink, A., Kalli, J., Pettersson, H., Kukkonen, J. and Stipa, T.: A modelling system for the exhaust emissions of marine traffic and its application in the Baltic Sea area, Atmos. Chem. Phys. Discuss., 9(4), 15339–15373, doi:10.5194/acpd-9-15339-2009, 2009.

Jalkanen, J. P., Johansson, L., Kukkonen, J., Brink, A., Kalli, J. and Stipa, T.: Extension of an assessment model of ship traffic exhaust emissions for particulate matter and carbon monoxide, Atmos. Chem. Phys., 12(5), 2641–2659, doi:10.5194/acp-12-2641-2012, 2012.

Johansson, L., Jalkanen, J.-P., Kalli, J. and Kukkonen, J.: The evolution of shipping emissions and the costs of regulation changes in the northern EU area, Atmos. Chem. Phys., 13(22), doi:10.5194/acp-13-11375-2013, 2013.

Johansson, L., Jalkanen, J. P. and Kukkonen, J.: Global assessment of shipping emissions in 2015 on a high spatial and temporal resolution, Atmos. Environ., 167, 403–415, doi:10.1016/j.atmosenv.2017.08.042, 2017.

Karasalo, I.: Exact finite elements for wave propagation in range-independent fluid-solid media, J. Sound Vib., 172, 671–688, 1994.

Karasalo, I., Östberg, M., Sigray, P., Jalkanen, J.-P., Johansson, L., Liefvendahl, M. and Bensow, R.: Estimates of source spectra of ships from long term recordings in the Baltic sea, Front. Mar. Sci., 4(JUN), doi:10.3389/fmars.2017.00164, 2017.

Kipple, B.: Southeast Alaska cruise ship underwater acoustic noise, NSWC Rep., (NSWCCD-71-TR-2002/574) [online] Available from: http://www.nps.gov/glba/naturescience/whale_acoustic_reports.htm#Acoustic, 2002.

Leaper, R., Renilson, M. and Ryan, C.: Shhh … do you hear that ?, J. Ocean Technol., 9(June 2015), 50–69, 2014.

Li, D-Q; Hallander, J.: Shipping and underwater radiated noise, SSPA Highlights, 14–16, 2015.

McKenna, M. F., Ross, D., Wiggins, S. M. and Hildebrand, J. A.: Underwater radiated noise from modern commercial ships, J. Acoust. Soc. Am., 131(1), 92–103, doi:10.1121/1.3664100, 2012.

Moore, S. E., Reeves, R. R., Southall, B. L., Ragen, T. J., Suydam, R. S. and Clark, C. W.: A New Framework for Assessing the Effects of Anthropogenic Sound on Marine Mammals in a Rapidly Changing Arctic, Bioscience, 62(3), 289–295, doi:10.1525/bio.2012.62.3.10, 2012.

Nedwell, J. R., Edwards, B., Turnpenny, A. W. H. and Gordon, J.: Fish and Marine Mammal Audiograms : A summary of available information, Subacoustech Rep. ref 534R0214, (September 2004), 281, 2004.

Nikopouloulos, A; Sigray, P; Andersson, M; Carlström, J. L. E.: BIAS Implementation Plan - Monitoring and assessment guiance for continuous low frequency sound in the Baltic Sea. [online] Available from: http://www.diva-portal.org/smash/get/diva2:1072183/FULLTEXT01.pdf, 2016.

Rolland, R. M., Parks, S. E., Hunt, K. E., Castellote, M., Corkeron, P. J., Nowacek, D. P., Wasser, S. K. and Kraus, S. D.: Evidence that ship noise increases stress in right whales, Proc. Biol. Sci., 279(1737), 2363–8, doi:10.1098/rspb.2011.2429, 2012.

Rowen, A. L.: Chapter 24. Machinery Considerations, in Ship Design & Construction, Vol 1, edited by T. Lamb, The Society of Naval Architects and Engineers (SNAME), Jersey City, NJ., 2003.

Smith, T. W. P., Jalkanen, J. P., Anderson, B. A., Corbett, J. J., Faber, J., Hanayama, S. ., O'Keeffe, E. ., Parker, S. ., Johansson, L. ., Aldous, L. ., Raucci, C. ., Traut, M. ., Ettinger, S. ., Nelissen, D. ., Lee, D. S. ., Ng, S. ., Agrawal, A. ., Winebrake, J., J.; Hoen, M. ., Chesworth, S. . and Pandey, A.: Third IMO GHG Study 2014., 2014.

Wales, S. C. and Heitmeyer, R. M.: An ensemble source spectra model for merchant ship-radiated noise, J. Acoust. Soc. Am., 111(3), 1211–1231, doi:10.1121/1.1427355, 2002.

Watson, D. G. M.: Practical Ship Design, Elsevier Science., 1998.

Wittekind, D. K.: A simple model for the underwater noise source level of ships, J. Sh. Prod. Des., 30(1), 1–8, doi:10.5957/JSPD.30.1.120052, 2014.

Yang, W.-C., Chou, L.-S., Jepson, P. D., Brownell, R. L., Cowan, D., Chang, P.-H., Chiou, H.-I., Yao, C.-J., Yamada, T. K., Chiu, J.-T., Wang, P.-J. and Fernández, a: Unusual cetacean mortality event in Taiwan, possibly linked to naval activities., Vet. Rec., 162(April 2016), 184–186, doi:10.1136/vr.162.6.184, 2008.

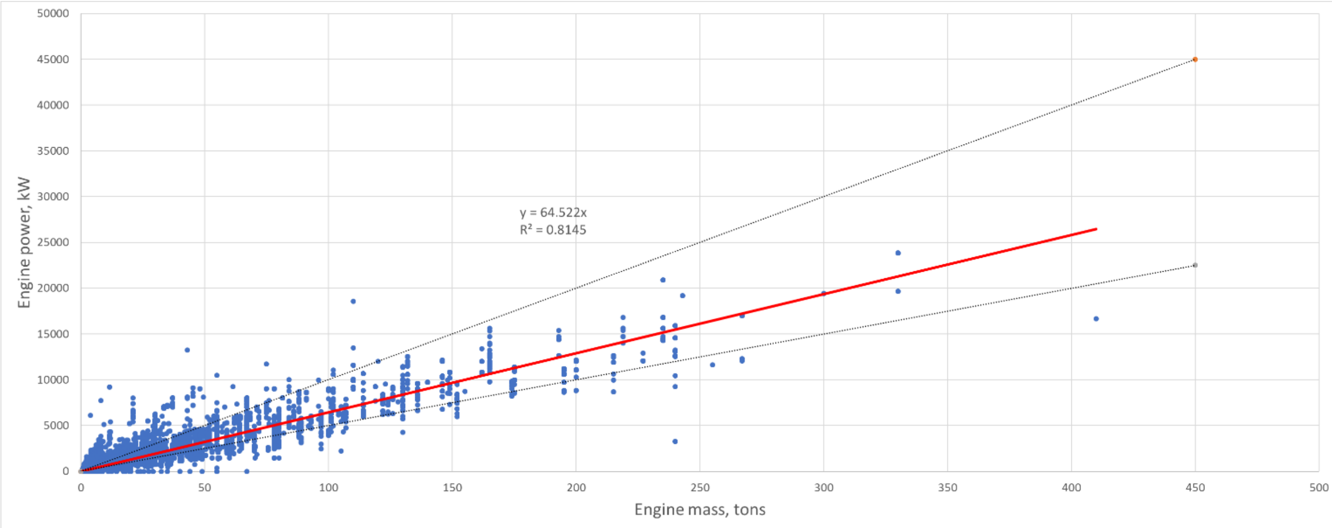

Figure 1 Predicted and actual main engine masses of 31 500 four stroke engines. The black lines represent the range given by Watson (Watson, 1998). The red line indicates the mass/power dependency used in this study for cases where engine mass could not be determined from engine catalogues.

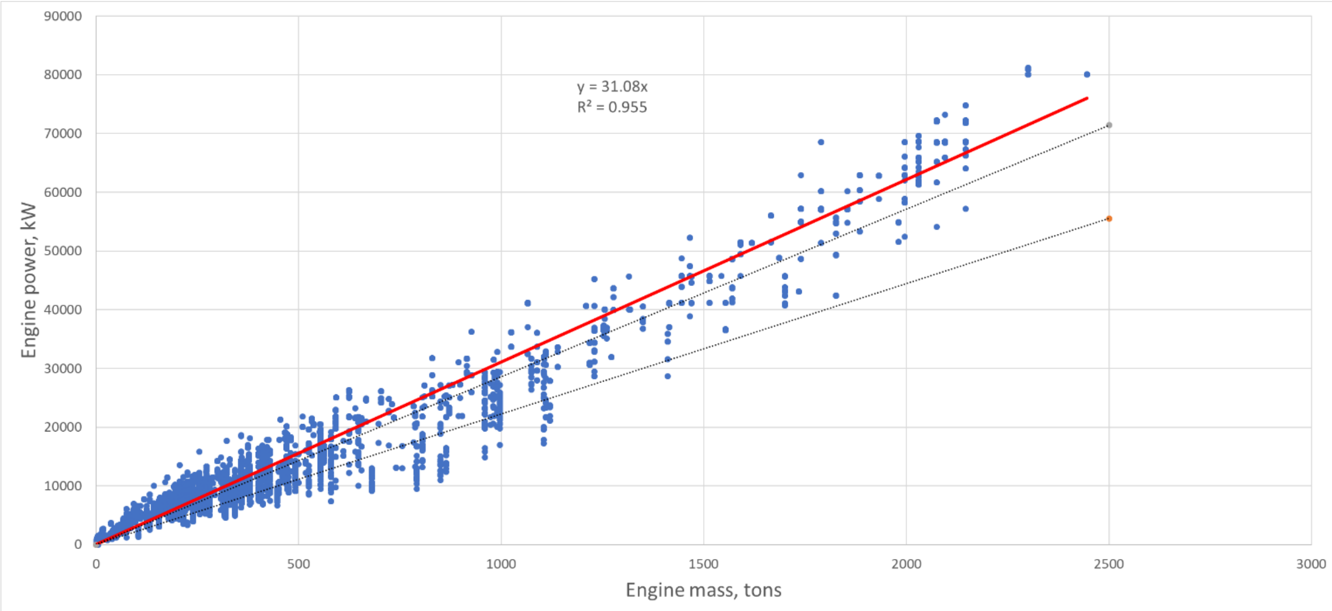

Figure 2 Predicted and actual main engine masses of 24 000 two stroke engines. The black lines represent the range given by Watson (2002). The red line indicates the mass/power dependency used in this study

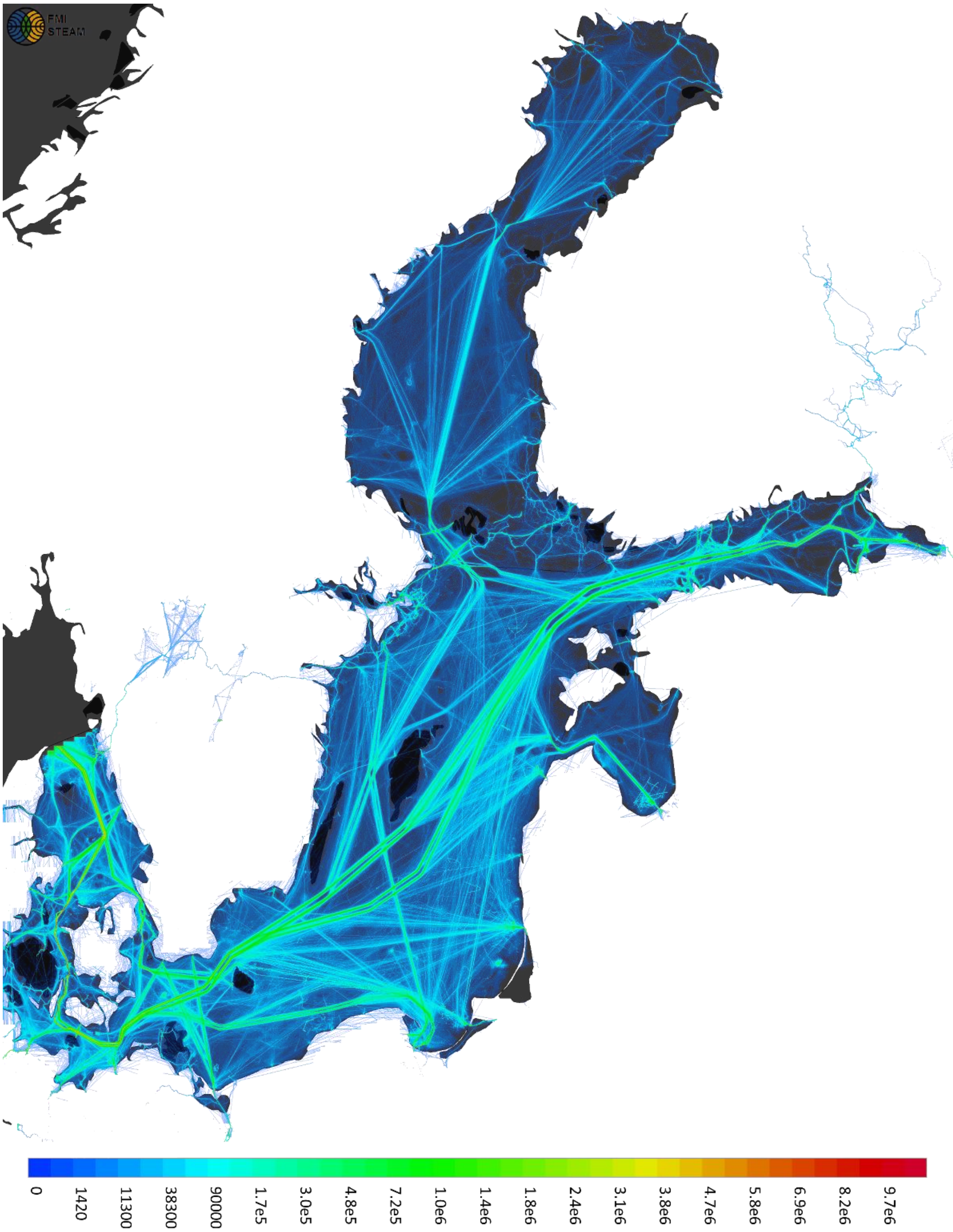

Figure 3 Noise source map for Baltic Sea shipping. This map indicates sum of sound energy in units of Joules per grid cell (cell area 0.32 km²) during the year 2015. This image represents the noise energy within the 125 Hz band (112-141 Hz).

5

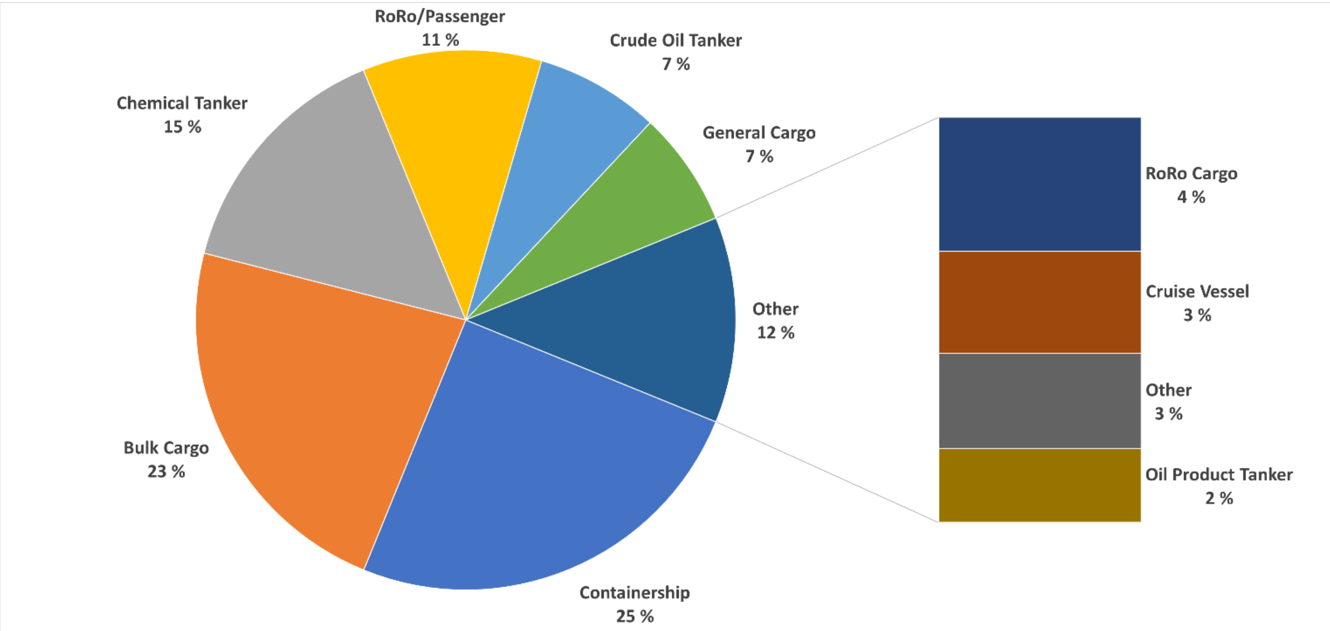

Figure 4 Contribution of different ship types to annual emissions of underwater noise energy in the 125 Hz band (112-141 Hz).

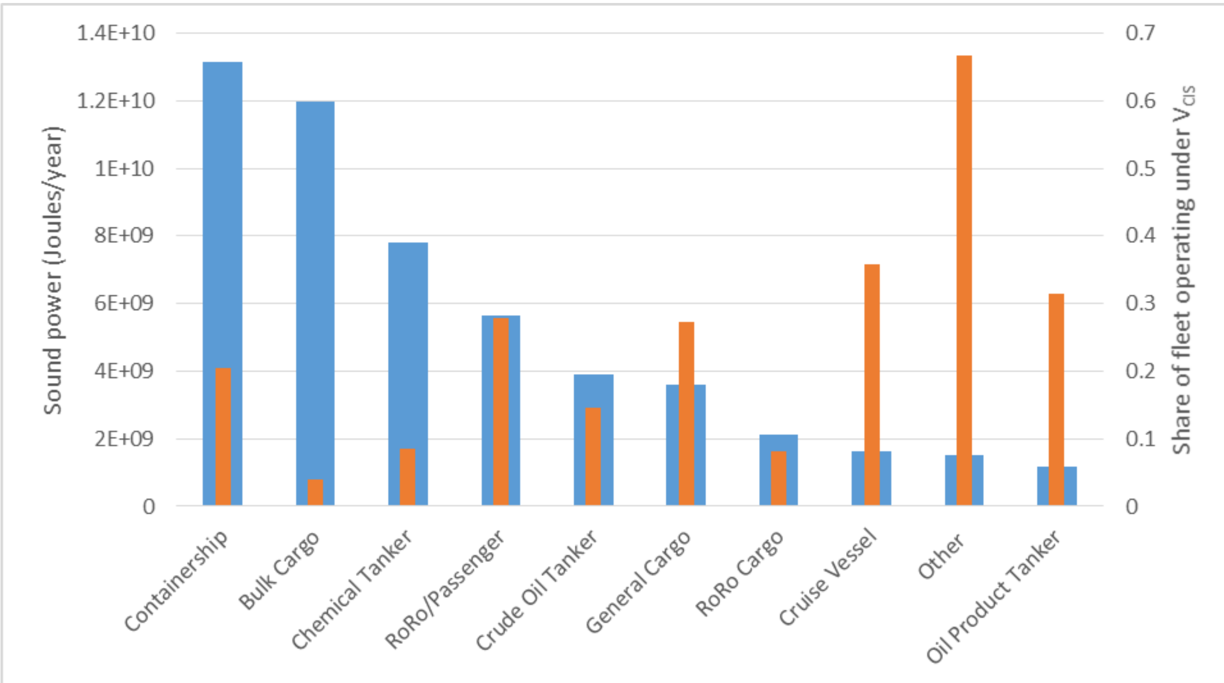

Figure 5 Noise energy emitted by different ship types in 125 Hz frequency band (in Joules per year; blue bars, left axis). The share of the fleet operating under cavitation inception speed is also indicated (orange bars, right axis). For example, containerships are the biggest source of the Baltic Sea fleet with 13 gigajoules of sound power emitted. Of the containership fleet, about 20% operate with speeds lower than their predicted cavitation inception speed.

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Table 1 Noise energy emitted by various ship types in the Baltic Sea area during 2015. The top ten contributors are reported, these represent over 90% of the noise energy emitted.

Type	Noise energy (GJ/a), 63 Hz	Noise energy (GJ/a), 125 Hz	Noise energy (GJ/a), 2 kHz
Containership	21.48	13.13	0.18
Bulk Cargo	24.04	11.98	0.18
Chemical Tanker	19.08	7.79	0.12
RoRo/Passenger	8.57	5.63	0.08
Crude Oil Tanker	13.66	3.90	0.06
General Cargo	7.50	3.61	0.06
RoRo Cargo	6.60	2.14	0.03
Cruise Vessel	2.78	1.63	0.02
Other	1.85	1.52	0.02
Oil Product Tanker	4.49	1.18	0.02
Total	118.05	57.78	0.86