DOI: 10.15480/882.9335

Eighth International Symposium on Marine Propulsors
smp'24, Berlin, Germany, March 2024

'PIANO': A physics-based semi-empirical source level model for fleet-scale ship URN prediction

Thomas Lloyd[1], Johanna Daniel[2], Johan Bosschers[1], Max Schuster[2]

[1]Maritime Research Institute Netherlands (MARIN), Wageningen, the Netherlands
[2]DW-ShipConsult, Schwentinental, Germany

ABSTRACT

Concern is growing about the impacts of continuous underwater radiated noise (URN) from ships on marine fauna. In anticipation of future regulation new tools are needed for the assessment of ship URN, covering predictions for individual vessels up to basin-scale soundscapes.

In this paper we describe the development of a physics-based semi-empirical source level model for predicting propeller cavitation noise and machinery noise of ships, which we call the PIANO model. The new model is designed to be applied efficiently at fleet scale, together with Automatic Identification System and ship particulars data, for the generation of sound maps. Furthermore, the model is suitable for use in forecast scenarios in which the effects of mitigation measures on URN are studied.

A description of the model is presented, together with an overview of the required input parameters. Improvements on the state-of-the-art are summarised. Results of model validation using measurements from the Enhancing Cetacean Habitat and Observation (ECHO) Program are reported. Overall the new model provides a higher degree of predictive capability compared to existing models while exhibiting similar levels of accuracy and uncertainty. Despite having been developed for sound mapping studies, it can also be used for early design stage URN predictions.

Keywords

underwater radiated noise; cavitation; machinery; source level; semi-empirical

1 INTRODUCTION

There is increasing attention on the impacts of continuous underwater radiated noise (URN) from ships on marine fauna (Duarte et al. 2021). Although no international regulations aimed at mitigating ship noise currently exist, URN is included in the Good Environmental Status assessment of the European Union's Marine Strategy Framework Directive (EU 2017), while the International Maritime Organization has recently updated its guidelines for the reduction of URN from ships (IMO 2023). In anticipation of future regulation it is important that various stakeholders develop or obtain relevant knowledge and capabilities for effective noise abatement, ranging from ship builders and operators to port authorities and regulatory agencies. As part of this effort new tools are needed for the assessment of ship URN, covering predictions for individual vessels up to basin-scale soundscapes.

In this paper we describe the development on a new physics-based semi-empirical source level (SL) model for predicting propeller cavitation noise and machinery noise (from both main and auxiliary engines) of ships, undertaken as part of NAVISON (Navis Sonus), a project funded by the European Maritime Safety Agency (EMSA). We call this new model the PIANO (Propulsion-Induced Acoustic Noise in Operating condition) model.

Ship point source models should be computationally efficient such that they can be applied in combination with Automatic Identification System (AIS) data on a fleet scale, allowing sound maps to be generated using the predicted source levels; see e.g. Kinneging (2023) where use was made of the JOMOPANS-ECHO model by MacGillivray & de Jong (2021). An additional requirement of the NAVISON project was that the model must be suitable for use in forecast scenarios in which the effects of various mitigation measures on URN are investigated.

The URN of a ship is mainly driven by its design and by its operational conditions. A review of existing models has been made in order to inform desirable improvements in the development of the PIANO model. Most of the existing source level models only make use of ship particulars available from AIS data such as ship type and ship length. Additionally, some consider operational parameters provided by the AIS data, which is limited to the ship speed in most cases. The PIANO model includes relevant ship design parameters such as propeller type and design, engine type and engine mountings, and wake field quality. In addition, operational conditions such as propeller speed and engine power are considered. Some of these parameters can be obtained from commercially available ship databases (equivalent data was provided by EMSA for this project), whereas data for other input parameters had to be derived from internal databases at DW-ShipConsult and MARIN.

As part of the model development, validation is performed using measured source level data from the Enhancing Cetacean Habitat and Observation (ECHO) Program as well as other cases available to DW-ShipConsult and MARIN. Additionally, a comparison is made with existing point source models to determine both the overall agreement between the data sets and the respective uncertainty levels. The limitations of the new model are also discussed.

2 SHIP NOISE MODELS

This section is intended to reflect the current state of available ship point source models, evaluate them, and suggest desirable improvements for the new model. The focus will be on the analysis of existing empirical and semi-empirical models, which can be used to predict the URN of many ships with little information on ship details and are therefore suitable for noise mapping.

2.1 Overview of existing point source models

A review of existing point source models was made, starting from the 1960s up to the present day (2022). Full details are provided in Lloyd et al. (2023). The parameters studied were the valid frequency range, estimated computational effort, whether or not the source levels are modelled as a function of ship speed and/or size, and whether machinery and/or cavitation noise mechanisms are modelled separately. The following are the main characteristics shared by most available models:

- Based on a small number of underwater noise measurements, or the measurements are very old (to the Second World War).
- Based on measurements in shallow water.
- The measured source levels are derived using simple propagation models.
- The characteristic hump in the cavitation noise spectrum is not modelled.
- There is no differentiation between different noise sources such as cavitation and engine noise.
- Most models use the same spectral slope as a function of frequency.
- Simple regression models are used.
- Two-stroke engines are not modelled by any model.
- The models are unsuitable for many different ship types.
- Only suitable for fixed pitch propellers (FPP) or controllable pitch propellers (CPP) at design condition, and not for CPPs in off-design condition.
- The models do not offer the possibility to examine noise reduction measures.

2.2 Details of key existing source models

Some key models for predicting ship noise are discussed here in more detail, as they provide the basis for the PIANO model.

2.2.1 Wales and Heitmeyer model

The Wales & Heitmeyer (2002) model is the first to focus on the source level rather than the radiated noise level (RNL). This back-calculation to a noise source in an unconstrained environment allows to position the source in different environments and to then calculate the propagation under specific and different environmental conditions, making it suitable for sound mapping studies.

2.2.2 JOMOPANS-ECHO model

MacGillivray and de Jong (2021) derived the JOMOPANS-ECHO (J-E) source level model from a regression analysis of the ECHO data set based on parameters included in the Research Ambient Noise Directionality (RANDI) model (Breeding et al. 1996) while making distinction between ship classes. The ECHO dataset used consists of 1862 source level measurements collected in Vancouver, Canada in 2017. The main parameters describing the noise levels are ship speed and ship length, where the ship speed is made non-dimensional using reference values that are ship type specific. The dependencies are taken identical to the values of the RANDI model, i.e., a speed dependency according to V^6 and a length dependency according to L^2. The spectral shape does not vary with ship speed or length but does vary with ship type.

2.2.3 Wittekind model

The model of Wittekind (2014) is unique in the sense that it distinguishes between machinery noise and propeller cavitation noise. The model considers four-stroke (4S) engines, the source level of which is calculated using the engine specific parameters: engine mass, type of engine mounting and number of operating engines. The model only represents the design state of the engine since the source level is calculated using the engine mass; the operating condition of the engine is not included. In addition, it only applies to four-stroke engines and does not include a function for two-stroke (2S) engines, although this was addressed recently by Daniel et al. (2022).

For propeller noise, a distinction is made between low-frequency cavitation noise and high-frequency noise. Both low- and high-frequency noise levels depend on ship speed, cavitation inception speed, and block coefficient whereas the low-frequency noise also depends on displacement. The inclusion of the cavitation inception speed makes the model easily adjustable to individual ships, but in general there is not much information available on the cavitation inception speed of merchant ships, which furthermore depends on details of ship wake and propeller geometry often only known to the propeller designer.

The low-frequency cavitation noise has a higher ship speed dependency (V^8) than the high-frequency cavitation noise (V^6), which is not confirmed by other models or by literature. The spectral shape does not vary with ship speed or any other ship parameter.

2.2.4 Empirical Tip Vortex model

Finally, the Empirical Tip Vortex (ETV) model of Bosschers (2018b) is a semi-empirical model that describes the noise of tip-vortex cavitation, which is based on the model by Raestad (1996). It is not intended to be used for creating ship sound maps, having been developed to assist propeller designers.

In this model, the non-dimensional noise level is related to the non-dimensional cavity size by regression analysis. The vortex cavity size is estimated using a computed value for the tip vortex strength combined with a simple vortex model that includes viscous effects, where the tip vortex strength is estimated by a boundary element method (BEM) that takes the detailed propeller geometry and ship wake into account. A spectral shape is assumed that consists of a combination of a low-frequency hump and a high-frequency region with constant slope, with the centre frequency of the hump depending on the vortex cavity size and cavitation number.

More recently semi-empirical models for sheet cavitation, leading-edge vortex cavitation, and tip-leakage vortex cavitation were also developed using the same approach (Lafeber et al. 2022).

2.3 Desired features and improvements of PIANO model

Based on the findings from Sections 2.1 and 2.2, it can be concluded that no single available point source model allows the effects of relevant changes in vessel propulsion system design and operating conditions on URN to be simulated. This implies that the models are not suitable for modelling different ship types nor for application when making forecast scenarios involving simulation of mitigation measures such as hull and propeller optimisation and/or cleaning (Lloyd et al. 2023).

A summary of the improvements which the PIANO model should offer over existing models is:

- Use a physics-based approach including parameters relating to ship design and operating condition, making it easier to model differences between ship types as well as perform forecast modelling.
- Model two-stroke engines, the most common engine type of the merchant fleet.
- Model CPPs at reduced pitch, aiming to increase accuracy at low ship speeds, for which URN due to cavitation is known to exhibit a different character than at design pitch.

These requirements combine several features from the J-E, Wittekind and ETV models in a single model, while also adding completely new features. Furthermore, the input data for the ETV-like cavitation noise model must be derived from readily available parameters, rather than BEM computations, which are too computationally expensive in the context of sound mapping.

3 DEVELOPMENT OF PIANO MODEL

The model was developed to predict the main contributors to merchant ship URN, i.e. machinery and cavitation noise. In the context of the NAVISON project, the model was to be applied for sound mapping studies covering five ship type categories: container ships; tankers and gas carriers; bulk and general cargo vessels; ro-ro (cargo and passenger) vessels; and cruise/passenger ships. The frequencies of interest are the 63 Hz and 125 Hz decidecade frequency bands, as specified in the Marine Strategy Framework Directive (EU 2017). Furthermore, the model was to be suitable for performing forecast scenario modelling involving URN mitigation, although this aspect is not covered further here.

A flow chart describing the PIANO model is provided in Figure 1. The model takes inputs from AIS and ship particulars data, as well as in-house databases (or regressions based thereon).

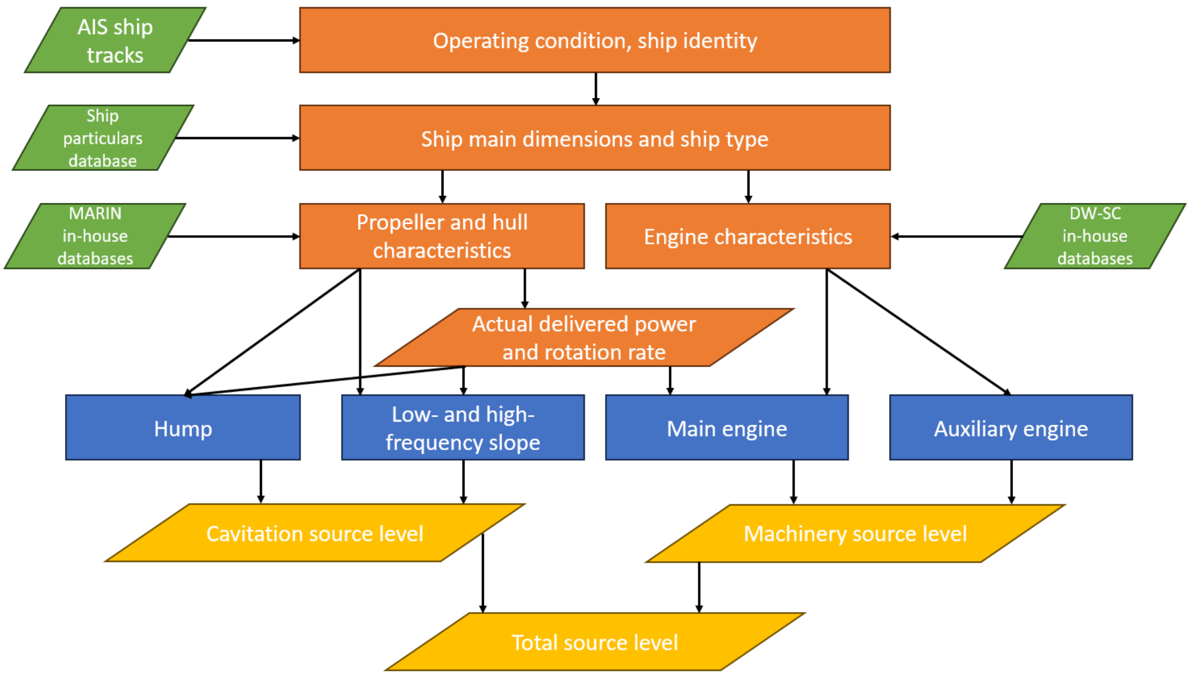

Figure 1: PIANO source level model flow chart. Model inputs shown in green; processes and intermediate results in orange; individual spectral components in blue; and outputs in yellow.

The total decidecade bandwidth source level in dB as a function of frequency in hertz is computed as:

$$L_S(f)\,[dB] = 10\log_{10}\left(10^{\frac{L_{S,2S}/L_{S,4S}(f)}{10}} + 10^{\frac{L_{S,AE}(f)}{10}} + 10^{\frac{L_{S,cav}(f)}{10}}\right), \quad (1)$$

where $L_{S,2S}/L_{S,4S}$ is the source level due to (two-stroke or four-stroke) main engines, $L_{S,AE}$ is the source level due to auxiliary engines and $L_{S,cav}$ is the source level from propeller cavitation. The following subsections describe how the contributions from propeller cavitation and machinery noise are obtained.

3.1 Propeller cavitation

3.1.1 Background

The most common forms of cavitation on merchant ship propellers are tip vortex cavitation and sheet cavitation. These are therefore the focus of the present model. Bosschers (2018a,b) previously developed a semi-empirical model for tip vortex cavitation (the ETV model), while a similar approach was later used for modelling sheet cavitation (Lafeber et al. 2022). Here we consider an extension of the ETV model such that it can be applied in the context of sound mapping studies, without explicity distinguishing between tip vortex and sheet cavitation source mechanisms.

3.1.2 Source levels

The propeller cavitation source levels in decidecade bandwidth levels are obtained from the narrowband levels as:

$$L_{S,cav}(f)\,[dB] = L_{S,cav,1Hz}(f) + 10\log_{10}(0.23156f), \quad (2)$$

where the narrowband source level spectrum can be written as:

$$L_{S,cav,1Hz}(f)\,[dB] = 10\log_{10}\left(\frac{p'(f)^2}{p_0^2}\right) + 10\log_{10}(N_{prop}). \quad (3)$$

Here $p'(f)^2$ is the mean square source pressure, p_0 the reference pressure, equal to 1 μPa, and N_{prop} is the number of propellers, where it is assumed that the sound radiated from each propeller is incoherent. Using rudimentary scaling arguments, the mean square source pressure can be written as

$$p'(f)^2 = K_p\left(\frac{f}{f_{bp}}\right)\rho^2 n^3 D^6, \quad (4)$$

where ρ is the fluid density (of water) in kg/m^3, n is the propeller rotation rate in hertz, and D is the propeller diameter in metres. Frequency is normalised by the blade passing frequency f_{bp} while K_p is the non-dimensional pressure power density coefficient. Computing the broadband source level spectrum consists of two main steps: predicting the peak value of K_p and the associated non-dimensional peak frequency f_p; and combining these with an assumed spectral shape. This can be expressed as

$$L_{S,cav,1Hz}(f)\,[dB] = 10\log_{10}\left(p'^2_{max}\right) + H(f) + 10\log_{10}(N_{prop}) + 120, \quad (5)$$

where p'^2_{max} is the peak mean square source pressure and $H(f)$ the spectral shape.

3.1.3 Non-dimensional hump peak parameters

In the original ETV model (Bosschers 2018b), the peak non-dimensional pressure power density coefficient was taken to be a function of the non-dimensional tip vortex cavity size (radius), raised to a power 2κ. This is rewritten here in terms of propeller-related quantities, following Bosschers (2018a), as:

$$K_{p,max} \propto \left(\frac{r_c}{D}\right)^{2\kappa} \propto \left(\frac{\tau K_T}{Z\sqrt{\sigma_n}}\right)^{2\kappa} Z, \quad (6)$$

while the peak frequency is a function of the same parameters:

$$\frac{f_p}{f_{bp}} \propto \frac{1}{\frac{r_c}{D}}\frac{\sqrt{\sigma_n}}{Z} \propto \frac{1}{\left(\frac{\tau K_T}{Z\sqrt{\sigma_n}}\right)}\frac{\sqrt{\sigma_n}}{Z}. \quad (7)$$

In Eqs. 6 and 7, r_c is the cavity radius, τ the maximum tip loading parameter, $K_T = T/\rho n^2 D^4$ the mean thrust coefficient with T the mean thrust, Z number of blades and σ_n the cavitation number, which is defined here as:

$$\sigma_n = \frac{2\left(p_c - p_v\right)}{\rho n^2 D^2} = \frac{2\left(p_{atm} + \rho g h_c - p_v\right)}{\rho n^2 D^2}. \quad (8)$$

The symbols p_c and p_v denote the local pressure at the cavity location and the vapour pressure of water respectively, while p_{atm} is atmospheric pressure and h_c the cavity immersion. In this work we estimate the thrust coefficient using basic propulsor performance theory, such that this parameter can be replaced by quantities including ship speed and Taylor wake fraction, and propeller diameter, rotation rate, efficiency and delivered power. The delivered power P_D in watts is estimated from the engine brake power P_{ME} by:

$$P_D = \eta_S \eta_G P_{ME}, \quad (9)$$

with η_S and η_G the shaft and gearbox efficiencies. Furthermore, we split the propeller maximum tip loading parameter into the product of two components:

$$\tau = \tau_w \tau_p, \quad (10)$$

with τ_w representing the effect of the wake peak and τ_p the blade design, i.e. mean tip (un)loading. Substituting these estimates into Eqs. 6 and 7 results in:

$$K_{p,max} = C_{p,cav}\left(\frac{\tau_w \tau_p \eta_O}{V(1-w_T)}\left(\frac{P_D}{D^2}\right) \times \frac{1}{\rho n D}\frac{1}{Z\sqrt{20(10+h_c)}}\right)^{2\kappa} Z \quad (11)$$

and

$$\frac{f_p}{f_{bp}} = C_{f,cav}\frac{20(10+h_c)\rho V(1-w_T)}{\tau_w \tau_p \eta_O\left(\frac{P_D}{D^2}\right)}, \quad (12)$$

where constants of proportionality $C_{p,cav}$ and $C_{f,cav}$ have been introduced. Written in this way, we aim to predict the peak non-dimensional pressure power density coefficient and non-dimensional frequency in terms of quantities which can be estimated from available data sources, including AIS, ship particulars databases and in-house databases. The peak mean square source pressure is obtained by substitution of Eq. 11 into Eq. 4.

3.1.4 Spectral shape

Following Bosschers (2018a,b), the spectral shape is expressed as the weighted power sum of two contributions:

$$H(f)\,[dB] = 10\log_{10}\left(\alpha 10^{\frac{H_h(f)}{10}} + (1-\alpha)10^{\frac{H_s(f)}{10}}\right), \tag{13}$$

where H_h relates to the characteristic hump and H_s is the slope function. The parameter α controls the weighting and is defined by $\Delta L_\alpha = 10\log_{10}(1-\alpha)$, where ΔL_α is the difference between the maximum of the two contributions, in dB. For the detailed formulations of the hump and slope functions, see Bosschers (2018a,b). The effect of the empirical constants and coefficients on the spectral shape is sketched in Figure 2, where the parameters α_h and α_l control the slopes of the high- and low-frequency parts of the spectrum and $\Delta L_{p,cav} = 10\log_{10}(C_{p,cav})$ and $C_{b,cav}$ control the height and width of the hump.

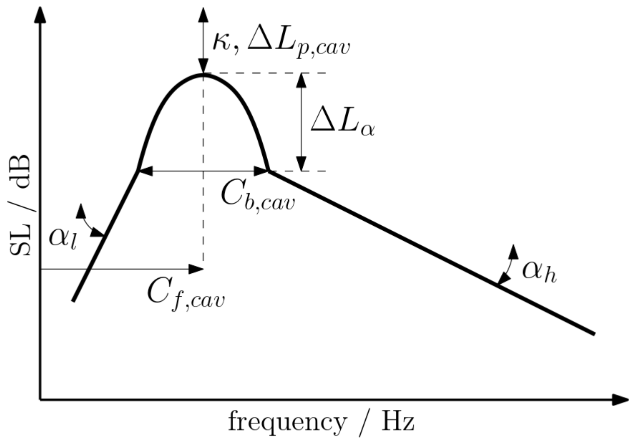

Figure 2: Schematic spectrum showing cavitation source level model tuning parameters and their effect on spectral shape.

3.1.5 Controllable pitch propellers

The model described above is valid for fixed pitch propellers (FPPs) at all ship speeds (above cavitation inception speed; CIS), and controllable pitch propellers (CPPs) operating at design speed (pitch). It is known that CPPs can experience different forms of cavitation at low ship speeds, when the propeller is operated at a constant rotation rate. This often results in a different spectral shape and higher noise levels than for FPPs (Traverso et al. 2017). In order to account for this effect, here we empirically tune the empirical constants $L_{p,cav}$, $C_{f,cav}$ and ΔL_α using full-scale URN measurement data for a general cargo ship operating at constant rotation rate and four propeller pitches. Instead of taking fixed values, these constants are modelled as a function of ship speed for all vessels equipped with a CPP.

3.2 Machinery noise model

3.2.1 Modelling approach

The PIANO machinery noise model is an extension of and improvement on the Wittekind (2014) model. The model predicts the underwater radiated noise (L_S) from the combination of the structure-borne noise from vibrating machinery (L_v) and a transfer function (TF) accounting for the engine mounting/isolation type and basic characteristics of the ship hull structure, which can be written simply as:

$$L_S\;[dB] = L_v + TF. \tag{14}$$

Figure 3 illustrates the transfer of structure-borne noise to URN.

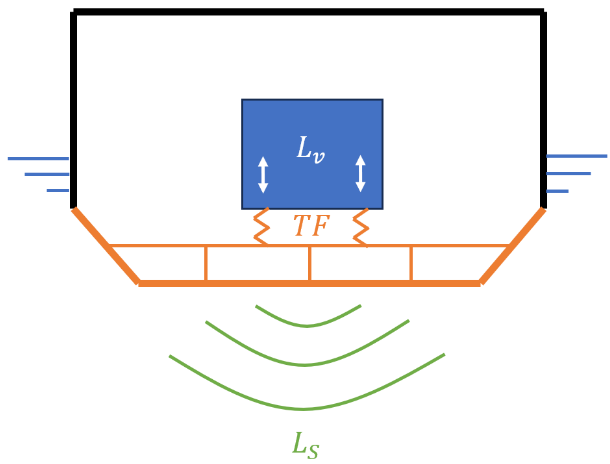

Figure 3: Schematic representation of machinery noise transfer function.

3.2.2 Model derivation

The structure-borne noise (SBN) can be modelled theoretically, as a function of the engine mass, installed power and rotation rate, assuming a similar ship structure in all cases, see e.g. Crocker (1997). This can be expressed in dB for main engines as (Crocker 1997):

$$\begin{aligned} L_v\left[dB, re.10^{-6}cm/s\right] =& -20\log_{10}(m_{ME}) \\ &+ 20\log_{10}(P_{ME,0}) \\ &+ 30\log_{10}\left(\frac{N}{N_0}\right) \\ &+ EM + 136, \end{aligned} \tag{15}$$

where m_{ME} is the engine mass in kilogrammes, $P_{ME,0}$ the installed power in kilowatts, N is the operating rotation rate in revolutions per minute (rpm), N_0 is the maximum rotation rate in rpm and EM accounts for the type of engine mounting. A similar expression holds for auxiliary engines (denoted by subscript AE in this work).

The source level due to vibrating machinery can be obtained by combining Eq. 15 with a theoretical estimation of the transfer function. This involves considering plates excited by a point force and can be written as:

$$\begin{aligned} L_S(f)\,[dB] =& L_v\left[dB, re.10^{-6}cm/s\right] \\ &+10\log_{10}(A\sigma)+10\log_{10}(n_p) \\ &+10\log_{10}(n_{ME})+87, \end{aligned} \tag{16}$$

where A is the radiating plate area in metres, σ the radiation efficiency (which is a function of frequency), n_p the number of radiating plates and n_{ME} the number of engines (sources). More details are provided in Lloyd et al. (2023). In this work, the relationships for the transfer function and structure-borne noise are derived empirically using DW-ShipConsult in-house databases. The transfer function as a function of frequency for two-stroke and four-stroke engines is obtained by regression using the difference between URN and SBN measurements for 37 ships. For the SBN, the following relationship is obtained, where $L_{v,ref}$ is a reference SBN level and $P_{ME,0,ref}$ a reference installed power:

$$\begin{aligned} L_S(f)\ \left[dB, re.1\mu Pa^2m^2\right] =& TF(f) \\ &+L_{v,ref}\left[dB,\ re.\,50\,nm/s\right] \\ &+7\log_{10}\left(\frac{P_{ME,0}}{P_{ME,0,ref}}\right) \\ &+28\log_{10}\left(\frac{N}{N_0}\right). \end{aligned} \tag{17}$$

Finally, the effect of elastic (resilient) mountings on the SBN of four-stroke engines was considered. Although this is a function of frequency, mounting type and machine weight, a simplified approach was required for the present application. Therefore a combination of values reported in literature (Crocker 1997; SNAME 2018) and DW-ShipConsult's own experience were used. The final values are EM = 20 dB for low-frequency mounts (four-stroke main engines) and EM = 22 dB for auxiliary engines. An additional 6.5 dB reduction was assumed for auxiliary engines due to their being mainly positioned on a 'tween deck. Furthermore, main engines were taken to be resiliently mounted after 2010, while for auxiliary engines this was assumed from 1980 onwards.

3.2.3 Final model

Based on the approach described in Section 3.2.2, the final models for the source level spectra in decidecade bandwidth levels for the various engine types are as follows. For two-stroke engines:

$$\begin{aligned} L_{S,2S}(f)\,[dB] =& 94.464+0.077135f-0.00040947f^2 \\ &-2.7\ln(f)+79+6\log_{10}\left(\frac{P_{ME,0}}{1000}\right) \\ &+28\log_{10}\left(\frac{N}{N_0}\right)+1.4\log_{10}\left(\frac{L_{bp}\cdot B}{208\cdot 32}\right), \end{aligned} \tag{18}$$

while for four-stroke engines this reads:

$$\begin{aligned} L_{S,4S}(f)\,[dB] =& 99-0.01f+10^7f^2+10\log_{10}(n_{ME}) \\ &+6.6\log_{10}\left(P_{ME,0}\cdot p_m\right)+11\log_{10}\left(\frac{P_{ME}}{P_{ME,0}}\right) \\ &+14\log_{10}\left(L_{bp}\cdot B\right)+EM. \end{aligned} \tag{19}$$

A similar expression as Eq. 19 is derived for auxiliary engines and reads:

$$\begin{aligned} L_{S,AE}(f)\,[dB] =& 99-0.01f+10^7f^2+10\log_{10}(n_{AE}) \\ &+6.6\log_{10}\left(P_{AE,0}\cdot p_a\right) \\ &+14\log_{10}\left(L_{bp}\cdot B\right)+EM-6.5. \end{aligned} \tag{20}$$

In Eqs. 18-20, L_{bp} and B are the ship length between perpendiculars and breadth respectively (both with units of metres), p_m and p_a are the power-to-weight factors for main and auxiliary engines, P_{ME} is the main engine operating power and $P_{AE,0}$ is the auxiliary engine installed power.

4 MODEL INPUTS

4.1 Input parameter sources

An overview of the required model inputs is given in Tables 1 and 2. Here, 'Particulars database' refers to a ship particulars database provided by EMSA which contains the IMO number of all relevant vessels and associated technical details. This allows detailed ship-specific information to be input to the model using the IMO number broadcast in the AIS messages. For full details of how the input parameters are obtained, see Lloyd et al. (2023).

Table 1: PIANO cavitation noise model input parameters.

Parameter	Source
Ship type	Particulars database
Propeller type	Particulars database
Ship speed (over ground)	AIS
Ship draught	AIS
Delivered power	$P_D \propto n^3$
Propeller diameter	MARIN database
Propeller rotation rate	$n \propto V$
Number of propeller blades	MARIN experience
Taylor wake fraction	MARIN database
Propeller open water efficiency	MARIN database
Propeller tip loading	MARIN database
Empirical constants	Experience/validation

Table 2: PIANO machinery noise model input parameters.

Parameter	Source
Ship length	Particulars database
Ship breadth	Particulars database
Elastic mounting factor	DW-SC experience
Rotation rate	$N \propto V$
Maximum rotation rate	Database
Number of auxiliary engines	Particulars database
Number of main engines	Particulars database
Power-to-weight factors	DW-SC database
Auxiliary power	IMO
Maximum auxiliary power	Particulars database
Main engine power	$P_D \propto N^3$
Main engine installed power	Particulars database
Main engine stroke type	Particulars database

In addition to the parameters in Tables 1 and 2, we estimate the cavitation inception speed using the formula proposed by Jalkanen et al. (2018) which is given by

$$V_{\mathrm{CIS}} = min\left\{max\left[\left(1.42 - 1.2C_B\right)V_s; 9\right]; 14\right\}, \quad (21)$$

where V_{CIS} is the cavitation inception speed in knots. Below this speed the cavitation noise model is switched off for ships with an FPP. Controllable pitch propellers are assumed to always cavitate. Furthermore, we assume that vessels with a speed over ground (SOG) of less than 3 knots are anchored (Faber et al. 2021), meaning that the only contribution to the total URN comes from auxiliary engines.

4.2 Input uncertainty estimate

Due to the large number of input parameters required by the model, many of which are derived empirically, it was considered necessary to estimate the model input uncertainty. This was done using data for a general cargo ship, with the uncertainty derived from the standard deviation of the various regressions made for the input parameters (or best estimate). Therefore the estimates are specific to a single ship type, but provide an initial indication of the dominant sources of uncertainty. Full details can be found in Lloyd et al. (2023). The average standard uncertainty expressed in decibels is shown in Figures 4 and 5 for the cavitation noise and machinery noise models respectively.

For the cavitation noise model, the largest contributors to the combined uncertainty are the quantities estimated empirically, such as the propeller diameter and Taylor wake fraction, and the propeller tip loading factor, which was derived using a limited in-house dataset. In the case of the main engine noise model, the operating rotation rate is the dominant source of uncertainty, since this quantity is derived using several other quantities (which are included in Figure 4). The high uncertainty for the number of operating auxiliary engines is due to there not being any information available for this parameter. However, we note that since the auxiliary engines do not have a large contribution to the total source level, we do not expect this source of uncertainty to contribute to the combined uncertainty in most cases.

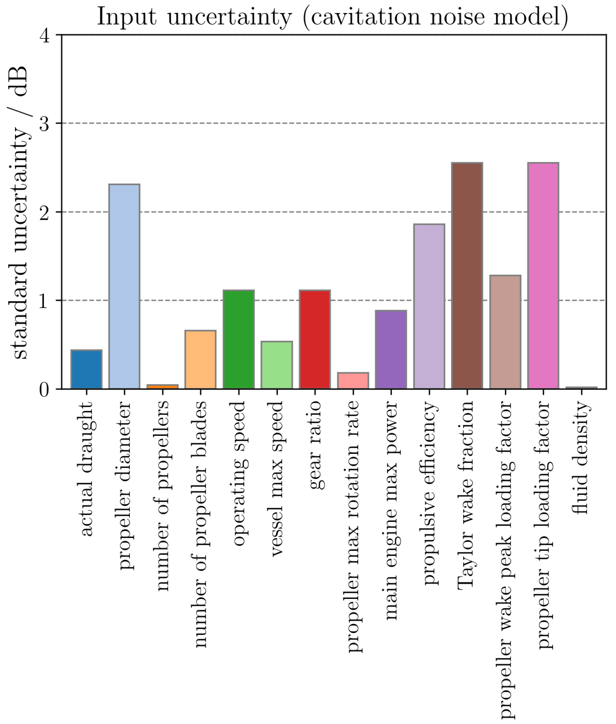

Figure 4: Input uncertainty estimation in dB for PIANO cavitation noise model, made using general cargo ship operating at design speed.

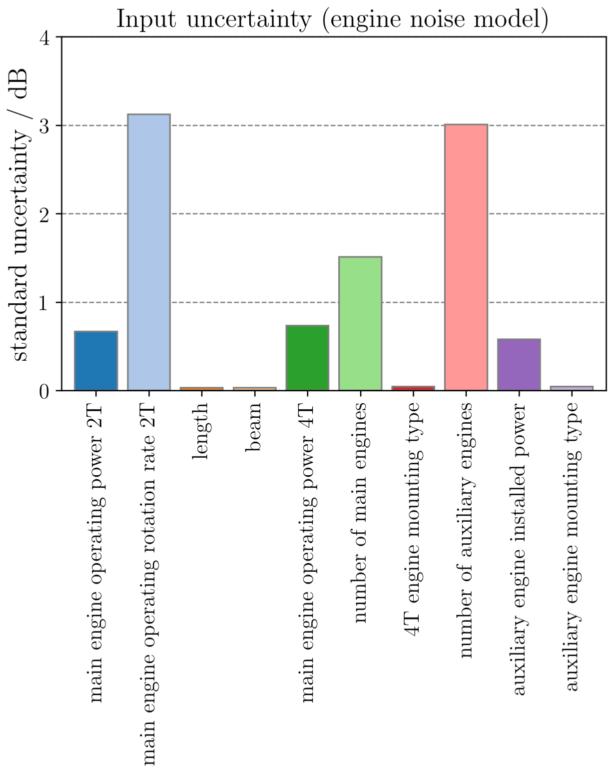

Figure 5: Input uncertainty estimation in dB for PIANO machinery noise model, made using general cargo ship operating at design speed.

The combined uncertainty for several combinations of the various sub-models is provided in Table 3, reaching up to 8.8 dB. MacGillivray & de Jong (2021) estimated the statistical uncertainty of the J-E model to be about 6 dB, while reporting that other similar models from the literature have a typical uncertainty of around 5 dB. The higher uncertainty of the PIANO model results from the high number of input parameters, some of which need to be estimated empirically, and is therefore not surprising. However, this is offset by the higher predictive capability of the model compared to many existing point source models.

Table 3: PIANO source level model estimated input uncertainty in dB.

Model	Combined input uncertainty / dB
Cav.	7.3
2S	3.4
4S	2.2
Aux.	2.4
2S + aux.	5.9
4S + aux.	5.3
Cav. + 2S	8.8
Cav. + 4S	8.5

5 DEMONSTRATION AND VALIDATION

In this section example results for individual vessels are presented - comparing the PIANO model to measurement data and predictions from existing source models - as well as error statistics from the model validation using thousands of sound measurements from the ECHO database.

5.1 Comparison with existing source models

Several of the improvements offered by the PIANO model are now demonstrated using two test cases of which measured source level spectra are available*. Two different ship types were selected: a container ship with two-stroke engine and fixed-pitch propeller; and a general cargo ship with four-stroke engine and controllable-pitch propeller. These two test cases were also used for initial tuning of the cavitation noise model, which is not presented here for brevity. Comparison is made with two of the key existing models used in the derivation of the PIANO model.

Source level spectra for the container ship at two speeds are shown in Figure 6. Overall, the PIANO model exhibits a good agreement with the measurement data, as does the J-E model. A major improvement of the PIANO model is the ability to model two-stroke engines at their operating condition, something which is demonstrated in Figure 6 when looking at the results of the Wittekind model for this case. Recall that the Wittekind model was only intended to model four-stroke engines based on their particulars.

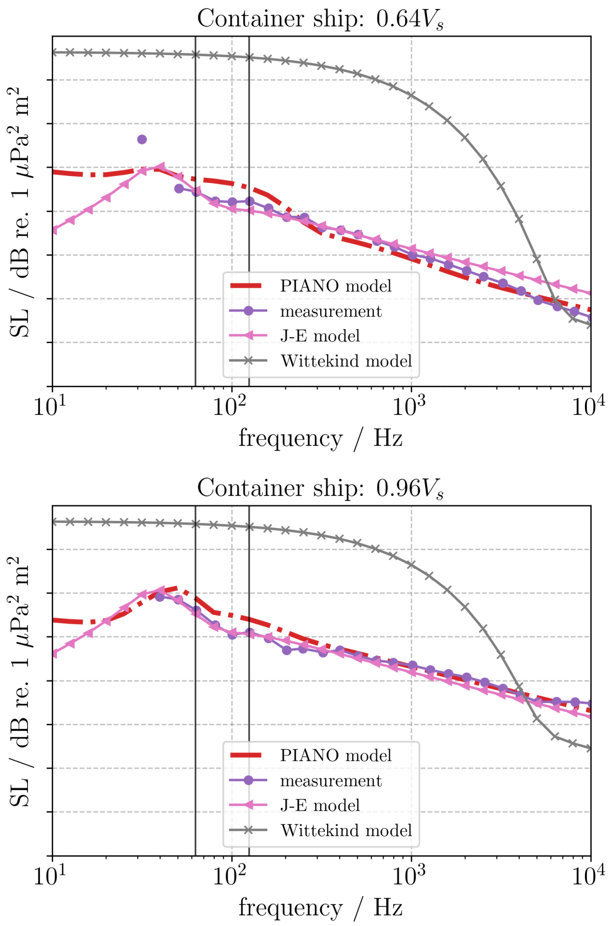

Figure 6: Comparison of decidecade band source level in dB as a function of frequency in Hz between the PIANO model and measurement data for container ship at two speeds. Scale divisions of the ordinate are 10 dB. The frequencies 63 Hz and 125 Hz are indicated by the vertical black lines.

Looking at the results for the general cargo ship in Figure 7, the comparison error of the Wittekind model is much smaller than for the container ship, although the operating condition of the main engine is not modelled. The main improvement when using the PIANO model in this case is the change in spectral shape, something which the J-E model does not include. For the 3.1 knots condition, the effect of a CPP operating at reduced pitch on the spectral shape can clearly be seen. The PIANO model has been extended to include this, while the J-E model predicts a much lower SL due to the very low ship speed. For the 10.2 knots condition, the difference in centre frequency of the cavitation hump between the PIANO and J-E models is observed. It is important to note that the J-E model does not model general cargo ships as a separate ship type, and that the prediction shown is for a bulk carrier. Furthermore, the peak in the measurement data between 10 and 20 Hz is likely due to tonal noise, which is not modelled by any of the models included in the comparison.

*The measurement data are available to MARIN through the Cooperative Research Ships (CRS). The absolute SL values are confidential.

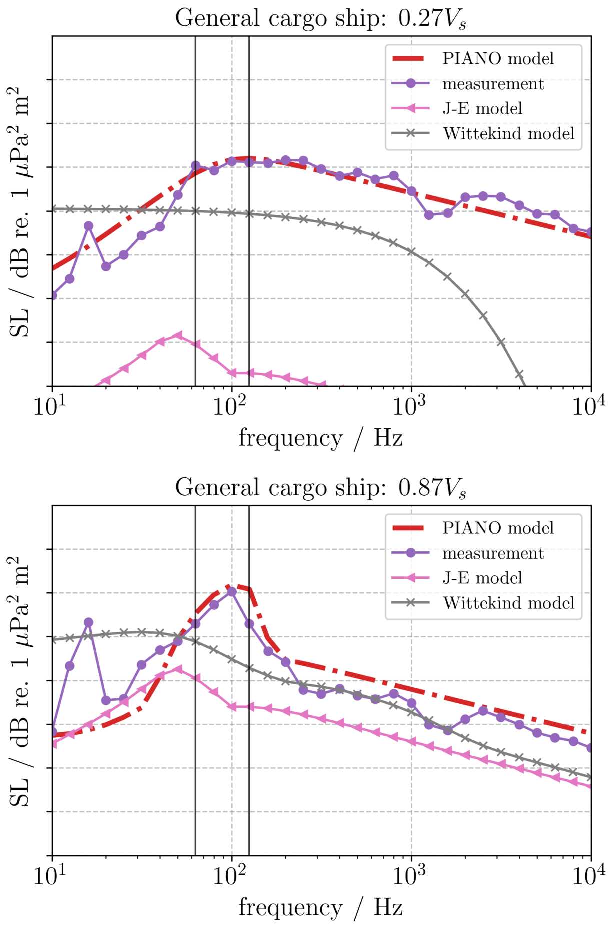

Figure 7: Comparison of decidecade band source level in dB as a function of frequency in Hz between the PIANO model and measurement data for general cargo ship at two speeds. Scale divisions of the ordinate are 10 dB. The frequencies 63 Hz and 125 Hz are indicated by the vertical black lines.

5.2 ECHO database validation and tuning

For further validation and tuning of the PIANO model, use was made of a database of 10,000 sound measurements from about 3000 anonymised vessels, provided by the Enhancing Cetacean Habitat and Observation (ECHO) Program. More information on the ECHO database can be found in MacGillivray et al. (2022).

5.2.1 Machinery noise validation

One application of the database was for validation of the machinery noise model. This was done by identifying measurements of vessels operating at low speed such that cavitation noise would not dominate the (low-frequency part of the) SL spectrum. Examples of these comparison are given in Figure 8, showing a good agreement at both 63 Hz and 125 Hz.

From the comparison of 29 vessels with two-stroke engines and 18 vessels with four-stroke engines, the mean and standard deviation of the comparison error at 63 Hz and 125 Hz was computed. The results are shown in Table 4, indicating that the mean error for two-stroke engines is higher than for four-stroke engines.

Table 4: PIANO machinery noise model comparison errors in dB for ECHO database.

Engine type	63 Hz		125 Hz	
	Mean	Std.	Mean	Std.
Two-stroke	3.2	2.7	3.0	2.3
Four-stroke	1.0	2.8	0.8	1.6

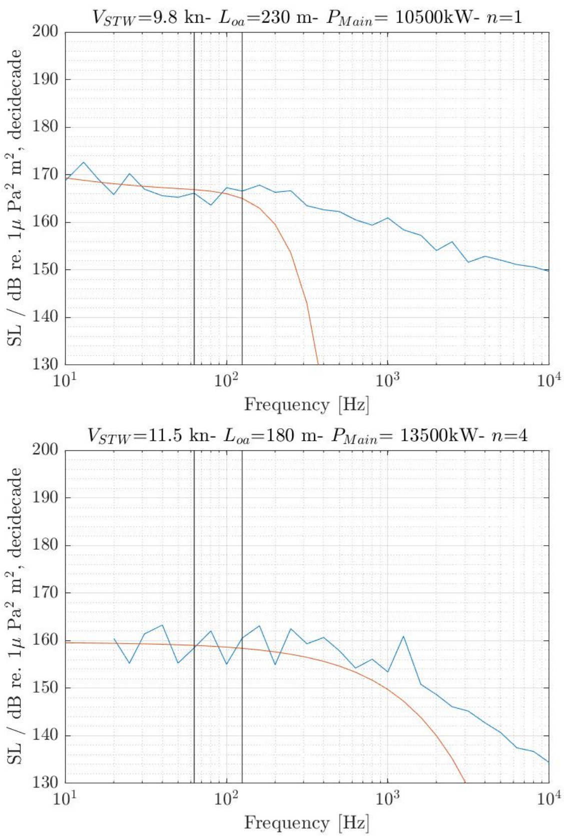

Figure 8: Comparison of decidecade band source level in dB as a function of frequency in Hz between the PIANO machinery noise model and measurement data, for selected vessels from ECHO database operating at low speed: two-stroke engine (top); four-stroke engine (bottom). Predictions are shown in red and measurements in blue. The frequencies 63 Hz and 125 Hz are indicated by the vertical black lines.

5.2.2 Cavitation model tuning

To test the accuracy of the PIANO model for a large range of individual vessels covering different ship types, the model was applied to almost 6000 measurements from the ECHO database (Lloyd et al. 2023). Comparison error statistics were compiled for each ship type, as well as across all vessels. The initial comparison error results, together with inspection of predictions for individual vessels, were then used to tune the cavitation noise model with the aim of reducing the comparison error. This was achieved by varying the parameters shown in Figure 2 per ship type. The most important changes made are adjusting the height and centre frequency of the cavitation hump, while for cruise ships the spectral shape was modified significantly.

The final comparison error in dB as a function of frequency for all measurements used is presented in Figure 9. The error statistics reported in the legend are the mean error at 63 Hz and 125 Hz, the mean and standard deviation of the error averaged across all frequencies and the mean error averaged up to 500 Hz and above 500 Hz. While the mean error is small (1.7 dB), the mean absolute error (not shown) was higher, at 5.6 dB for all vessels. However, this is similar to the J-E model, for which 5 dB was reported (MacGillivray & de Jong 2021).

The mean standard deviation of 7.1 dB appears acceptable when compared to about 6 dB for the J-E model, meaning the standard deviation has not increased significantly relative to existing (simpler) models. Furthermore the standard deviation lies below the estimated input uncertainty, meaning the model can be considered validated based on the available data.

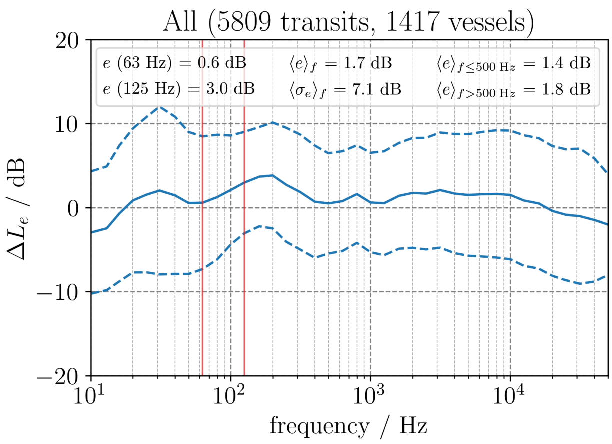

Figure 9: Comparison error in dB as a function of frequency in Hz between tuned PIANO model and measurement data, computed using all selected vessels from ECHO database. Solid blue line shows mean comparison error, dashed lines mean plus and minus one standard deviation. The frequencies 63 Hz and 125 Hz are shown by the red lines.

5.2.3 Example spectra

Finally, example SL spectra for two ship types are provided, comparing the PIANO model results to those from the ECHO database. This is shown in Figures 10 and 11, in which the contributions of the different source mechanisms to the total SL are included. The estimated vessel operating condition is also indicated in each figure.

The bulk carrier example displays a very good agreement between prediction and measurement, particularly below 500 Hz. The relative contributions of cavitation and machinery noise in this frequency range appear to be well modelled. From Figure 10 it can also be seen that the peak source level of the hump compared to that of the constant slope part of the spectrum has been increased. For bulk carriers, ΔL_α takes a value of 14 dB, compared to the original default value of 7 dB.

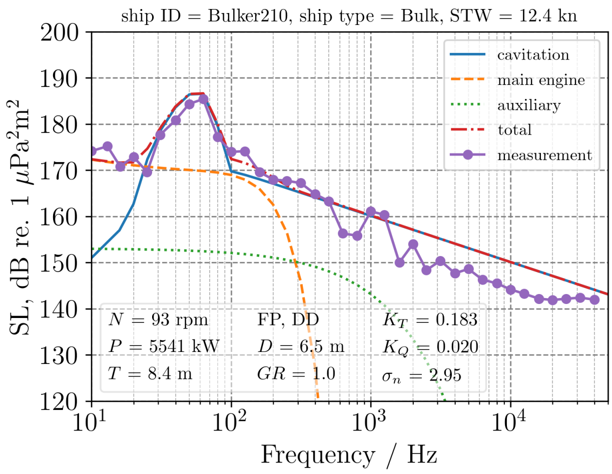

Figure 10: Example prediction using PIANO model compared to ECHO database measurement data for a bulk carrier. Decidecade band source level in dB as a function of frequency in Hz.

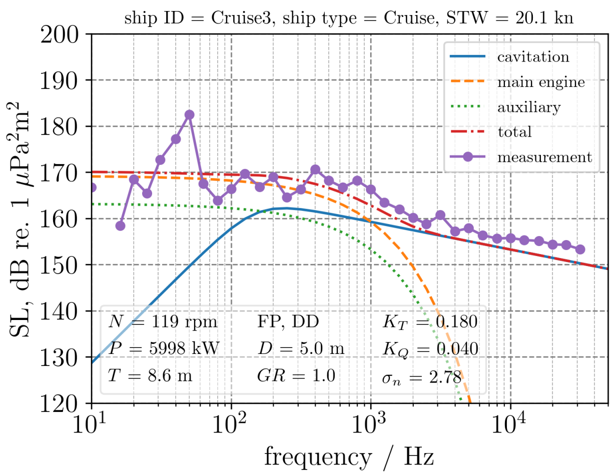

Figure 11: Example prediction using PIANO model compared to ECHO database measurement data for a cruise ship. Decidecade band source level in dB as a function of frequency in Hz.

Figure 11 clearly demonstrates the quite different spectral shape often seen for cruise ships compared to other vessel types, due to the difference in propulsion system and the design requirement of low onboard noise levels, resulting in less propeller cavitation. The PIANO model has been tuned to remove the cavitation hump, while the high-frequency slope has been made shallower, although we do not yet have a physical explanation for the latter effect. For this case, machinery noise dominates the total SL spectrum across a wider frequency range compared to the bulk carrier. The high measured SL in the 500 Hz decidecade frequency band may be due to machinery tonals, which are not modelled, resulting in a larger comparison error at this frequency.

6 DISCUSSION

The new PIANO model represents a large improvement on existing point source models for ship URN. Despite this, the model has some limitations, which are discussed further here.

Regarding the cavitation noise model, it was not possible to derive regressions for all input parameters, therefore we rely on experience, assumptions and simplifications for some variables. Furthermore some parameters are a function of ship type only, which does not represent the reality that ship designs within a certain class will vary. These two factors serve to increase the model uncertainty.

We also make use of the ship draught reported in AIS, which may be erroneous (notwithstanding basic checks included in our own data processing). This parameter is also reported as a single value, meaning that vessel trim cannot be derived. Therefore trim effects on the propeller operating condition are not modelled.

Due to the specific ship types and frequencies of interest included in the NAVISON project, the machinery noise model focuses on low-frequency noise. Therefore high-speed engines are not modelled, nor is URN from other types of machinery, such as gearboxes or alternative propulsion systems.

The modelling of resilient mountings was simplified considerably due to a lack of detailed information for individual vessels. Mounts are assumed to perform equally well at all frequencies, which is not the case in practice, where their performance depends on the frequency relative to the natural frequency of the mount.

Finally, the model only accounts for broadband URN; no tonal contributions are included. These can be strong at certain frequencies for certain ship types, which reduces the model accuracy, while also potentially complicating model validation based on decidecade bandwidth spectra.

7 CONCLUDING REMARKS

This paper details the development and validation of a new physics-based semi-empirical source level model for predicting underwater radiated noise from merchant vessels – the PIANO model. The model covers two main contributions to continuous broadband noise from ships, propeller cavitation, and the engines, and is designed to be used together with AIS data and ship databases for generating source level information as part of sound mapping studies.

Having studied limitations of existing point source models for ship URN, desirable features of the new model were identified, which is based on the ETV and Wittekind models. Improvements offered by the PIANO model include: modelling of two-stroke engines; modelling of controllable pitch propellers; main engines and propeller modelled at operating condition; and inclusion of several ship design parameters, enabling mitigation measures to be modelled.

Uncertainty estimation and model validation was performed. The uncertainty was found to be slightly higher than similar estimates provided in the literature for existing point source models, which is explained by the higher number of input parameters required. This is offset by the enhanced predictive capabilities of the model. At 63 Hz and 125 Hz the comparison error for most vessels was within 3 dB when applying the model to the ECHO database. Furthermore, the mean comparison error was comparable to that reported for the JOMOPANS-ECHO model, while the mean standard deviation of the comparison error was less than the estimated uncertainty for most of the ship types studied.

Future work will focus on the application of the model to forecast scenarios involving both technical and operational URN mitigation measures.

ACKNOWLEDGEMENTS

This work was performed as part of the NAVISON (Navis Sonus) project, funded by the European Maritime Safety Agency, project number EMSA/OP/18/2021. The other project partners and contributors were JASCO Applied Sciences (Deutschland) GmbH and the Enhancing Cetacean Habitat and Observation (ECHO) Program, Vancouver Fraser Port Authority.

The full-scale measurement data for the container and general cargo ship cases was made available to MARIN through Cooperative Research Ships (CRS). Additional anonymised vessel source level data used in this research was provided by the ECHO Program. Collection of the ECHO source level database is supported by the Government of Canada

REFERENCES

Bosschers, J., 2018a. Propeller tip-vortex cavitation and its broadband noise. Ph.D. thesis, University of Twente.

Bosschers, J., 2018b. ‘A semi-empirical prediction method for broadband hull-pressure fluctuations and underwater radiated noise by propeller tip vortex cavitation’. Journal of Marine Science and Engineering, **6**(2), p. 49.

Breeding, J. E., Pflug, L. A., Bradley, M. H., Walrod, M. H. & McBride, W., 1996. ‘Research Ambient Noise Directionality (RANDI) 3.1 - Physics description’. Tech. rep., Naval Research Laboratory, USA. Publication Title: NRL/FR/7176-95-9628.

Crocker, M. J., 1997. Encyclopedia of Acoustics, vol. 3. Wiley-Interscience.

Daniel, J. M., Schuster, M. G., Andresen-Paulsen, G., Holz, F., Wittekind, K. & Ehlers, S., 2022. ‘An advanced prediction model for underwater noise emissions of ships’. Journal of Ship Production and Design, **38**(4), pp. 220–238.

Duarte, C., Chapuis, L., Collin, S., Costa, D., Eguiluz, V., Erbe, C., Halpern, B., Havlik, M., Gordon, T., Merchant, N., Meekan, M., Miksis-Olds, J., Parsons, M., Predragovic, M., Radford, A., Radford, C., Simpson, S., Slabbekoorn, H., Staaterman, E., Opzeeland, I. V., Winderen, J., Zhang, X. & Juanes, F., 2021. ‘The soundscape of the anthropocene ocean’. Science,

371(583).

EU, 2017. ‘Commission decision (EU) 2017/848 of 17 May 2017 laying down criteria and methodological standards on good environmental status of marine waters and specifications and standardised methods for monitoring and assessment, and repealing Decision 2010/477/EU’. Official Journal of the European Union, **125**(May), pp. 43–74.

Faber et al., 2021. ‘Fourth IMO GHG Study’. International Maritime Organization.

IMO, 2023. ‘Revised guidelines for the reduction of underwater radiated noise from shipping to address adverse impacts on marine life (MEPC.1/Circ.906)’. Tech. rep.

Jalkanen, J.-P., Johansson, L., Liefvendahl, M., Bensow, R., Sigray, P., Östberg, M., Karasalo, I., Andersson, M., Peltonen, H. & Pajala, J., 2018. ‘Modelling of ships as a source of underwater noise’. Ocean Science, **14**(6), pp. 1373–1383.

Kinneging, N., 2023. ‘Joint monitoring programme of ambient noise North Sea (Jomopans): Opinion paper on continuous noise pollution’. Journal of Sea Research, **195**(June), p. 102414.

Lafeber, F. H., Bosschers, J., Lidtke, A., Lloyd, T., van Wijngaarden, E. & Moulijn, J., 2022. ‘Prediction of underwater radiated noise from propeller cavitation during concept design’. Proceedings of 7th Symposium on Marine Propulsors. 17th-21st October, Wuxi, China.

Lloyd, T. P., Daniel, J., Bosschers, J. & Schuster, M., 2023. ‘NAVISON Task 1.1 progress report: Development of a semi-empirical source level model for machinery and cavitation underwater radiated noise from ships’. Technical report by MARIN and DW-ShipConsult for European Maritime Safety Agency 02912.

MacGillivray, A. & de Jong, C., 2021. ‘A reference spectrum model for estimating source levels of marine shipping based on Automated Identification System data’. Journal of Marine Science and Engineering, **9**(4), p. 369.

MacGillivray, A. O., Ainsworth, L. M., Zhao, J., Dolman, J. N., Hannay, D. E., Frouin-Mouy, H., Trounce, K. B. & White, D. A., 2022. ‘A functional regression analysis of vessel source level measurements from the Enhancing Cetacean Habitat and Observation (ECHO) database’. The Journal of the Acoustical Society of America, **152**(3), pp. 1547–1563.

Raestad, A. E., 1996. ‘Tip vortex index - An engineering approach to propeller noise prediction’. The Naval Architect, **11**.

SNAME, 2018. ‘Design guide for shipboard airborne noise control’. Technical and Research Bulletin 3(37).

Traverso, F., Gaggero, T., Tani, G., Rizzuto, E., Trucco, A. & Viviani, M., 2017. ‘Parametric analysis of ship noise spectra’. IEEE Journal of Oceanic Engineering, **42**(2), pp. 424–438.

Wales, S. C. & Heitmeyer, R. M., 2002. ‘An ensemble source spectra model for merchant ship-radiated noise’. The Journal of the Acoustical Society of America, **111**(3), pp. 1211–1231.

Wittekind, D. K., 2014. ‘A simple model for the underwater noise source level of ships’. Journal of Ship Production and Design, **30**(1), pp. 7–14.