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Methodology for noise source modelling and its application to Baltic Sea shipping

Deliverable D4.1 of the BONUS SHEBA project

Mattias Liefvendahl, Andreas Feymark and Rickard Bensow

Department of Shipping and Marine Technology
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1
Introduction

Commercial shipping is a major source of noise in the sea, and it is associated with adverse effects on the marine environment. In recent times, this has received increased attention and the European Commission and the International Maritime Organization have initiated several initiatives to achieve a better understanding of underwater noise from shipping.

The present study, on noise source modelling, is carried out within the SHEBA[1,2]-project, funded by BONUS[3]. This project addresses many environmental aspects of shipping in the Baltic Sea region, and includes one work package for the investigation of noise from shipping. A review of ship noise source models is presented in this report, and lines of development are suggested for a methodology for noise source modelling suitable for Baltic Sea shipping. The proposed ship noise source modelling will be implemented in the software STEAM, [12], used and developed at FMI[4]. The STEAM software relies on ship operating information form the Automatic Identification System (AIS). In chapter 2, the framework of the noise source modelling is described. The connection to noise measurements for validation, sound propagation modelling, and the study of effect and impact on fish and marine mammals, is also described in that chapter.

For the evaluation of the noise models reviewed in the present report, only open data will be used. Very large data sets concerning radiated noise from ships are not available for the open research community due to commercial and military restrictions. It is generally recognized that there is a need for improvement of publicly available databases of ship noise of high quality, and with well-documented measurement procedures, [14, 9]. The first major ship noise source data set, [10], was obtained from surface ship noise measurements made on American, Canadian and British ranges during the second world war (WW2). The report [10] was written in 1945, was was declassified in 1960 and was used for development of classical source models, [17], see section 3.1 for a description. The report is still however not publicly available for the research community[5], which clearly illustrates how sensitive and important this type of measurements are considered to be by the military. Other studies, which employ significant measurement data sets for noise source modelling, reviewed in this report include Arveson and Vendettis (2000) [4], Wales and Heit-

[1]Sustainable SHipping and Environment of the BAltic Sea region (SHEBA)

[2]`www.bonusportal.org/projects/research_projects/sheba`

[3]Baltic Organizations' Network for Funding Science (BONUS)

[4]Finnish Meteorological Institute (FMI)

[5]"Distribution Code - C - 12 - U.S.GOVT. and U.S.GOVT.CONTRACTORS ONLY", when requested in 2015 from Defence Technical Information Center (DTIC), USA.

meyer (2002) [20], Kipple (2002) [13], McKenna et al.(2012) [14], and the noise source modelling and database generation within SONIC [8, 9]. Furthermore, there is currently significant activity in the european projects SONIC[6][3], AQUO[7][1], and BIAS[8][2]. These developments will be followed closely within SHEBA, and relevant improvements will be incorporated in the further developments.
In chapter 2, the requirements on the model are discussed, together with the framework into which the model will be integrated. The considerations lead to a monopole model for the ship source spectrum, for which no directivity is taken into account. In chapter 3, a review is given of models which may be suitable. The use of AIS-data, or similar data from additional sources, for model parameter determination, is discussed in chapter 4. An overview of model validation, using noise measurement data, is given in chapter 5. The report is concluded with a brief summary and a set of recommendations for the further work on noise modelling within the SHEBA-project.

[6]SONIC project, EU 7th Framework Programme, Grant agreement No. 314394, 2012-2015
[7]AQUO project, EU 7th Framework Programme, Grant agreement No. 314227, 2012-2015
[8]BIAS project code: BIAS LIFE11 ENV/SE/000841, 2012-2016

2

Framework for the ship noise source modelling

The focus of the present study is commercial shipping. The primary consideration is then the modelling of radiated noise from tankers, container ships, bulk carriers and passenger ships. The importance of other ship types, from the perspective of the SHEBA project, should also be considered. Concerning operating conditions, the most important case is considered to be transit at service speed, which implies a dominant contribution of the propeller cavitation noise. The importance of other operating conditions should also be considered.

An overview of noise generation mechanisms, and their contribution to radiated noise, is given in section 2.1. The full frequency range, from low ($\sim 10\,\mathrm{Hz}$) to high frequencies ($\sim 10^4\,\mathrm{Hz}$), is discussed. As explained in the corresponding section, the radiated noise spectrum is only considered in the broad-band sense. The framework for noise source modelling, for the applications considered in the SHEBA-project, leads to certain requirements and restrictions. In section 2.2 these constraints on the noise modelling are described. This section is preparatory to the review, in chapter 3, of noise source models within the category of interest.

2.1 Noise generation mechanisms

In the context of ship design and operation, noise can be considered from three distinct perspectives: (i) Underwater radiated noise; (ii) Noise onboard the ship, with a view to crew and passenger comfort, and; (iii) Self-noise, by which is meant the interference, of noise generated by the ship, with acoustic sensors operated on the ship. Self-noise is mostly important for specialized vessels designed for research or military purposes, and is out of the scope of the present study. Control of onboard noise levels have for a long time been a significant design requirement. Due to transmission and propagation of noise, the onboard noise is however completely different from the radiated noise. Hence, onboard noise is also out of this scope and only radiated noise is considered. It is to be noted that radiated noise traditionally have not been considered during design of commercial ships. For certain types of military ships, on the other hand, low levels of radiated noise are critical. As discussed in the introduction, it is only recently that requirements on radiated noise have reached some level of priority for commercial shipping. Next, the different noise mechanisms, and their contribution to the radiated noise, are discussed, in-depth treatments can be found in [17, 6].

SSPA	Kavitationsutbredningar vid försök med olika hydrofon-placeringar		Bilaga 7 Allm. rap.nr 52
beteckning i bilagor	(bladläge 20°)	σ	J
A	kav.fritt	36.71	0.515
B		17.88	"
C		13.17	"
D	+ trycksidekav.	8.76	"

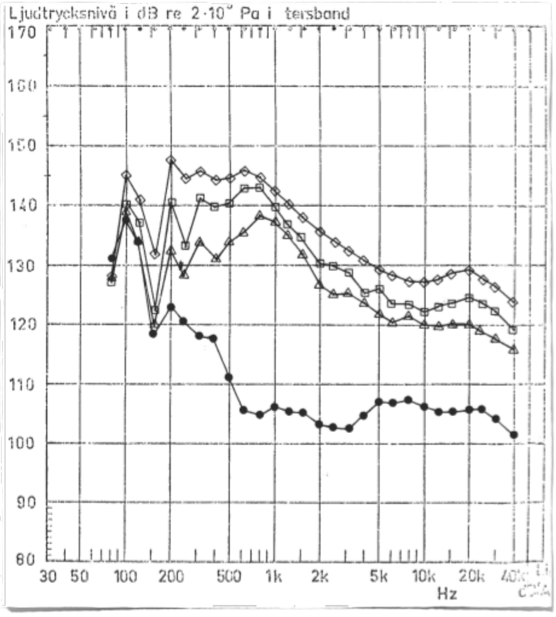

Figure 2.1: Developement of propeller blade cavitation, and associated noise, with decreasing cavitation number σ, four conditions A-D. To the left, the maximum cavity extent on the blade is scetched for the different cases. To the right, the corresponding sound-pressure spectrum levels for the four conditions, measured in a towing tank. Figures reproduced with permission from [5].

Generally, for commercial ships at service speed, cavitation at the propeller is the dominating noise source, throughout the spectrum. The propeller cavitation depends on the loading on the blades, and the flow environment at the propeller location. Generally the inflow to the propeller (wake field) is turbulent, and the time-averaged wake field contains significant non-uniformities, and both these properties lead to blade-load fluctuations. The fundamental frequency peak is determined by the blade-rate. A typical propeller shaft RPM$\sim$100, and 4-6 propeller blades, correspond to a blade rate in the order of 10 Hz. Due to the turbulent inflow to the propeller blade, and the complex dynamics of cavitation, a wide range of harmonics of the fundamental frequency are also present.

At high frequencies, above say 500 Hz for large ships, cavitation causes a broadband noise. Classically, the spectrum level is considered to decay approximately 20 dB for each frequency decade. Other models for the decay have however also been proposed, see chapter 3. Measurement data clearly indicate a relatively uniform decay for this noise contribution [17, 19, 9, 4, 20, 13]. In the intermediate frequency range, the propeller cavitation noise is affected by both mechanisms discussed above, and its modelling is less well understood [4, 11, 21].

At lower speeds than the service speed, there is less cavitation, and below the cavitation inception speed there is no contribution to noise from this source, which is dominant at normal transit condition. The results shown in figure 2.1 illustrates the sharp decrease in propeller noise below cavitation inception speed. Thus, at low speed operating condition, other noise sources are the main contributions to the radiated noise. These sources are: (i) Machinery noise, from propulsion (diesel

engine, gears) and auxiliary (generators, pumps etc.) machinery; (ii) Vibrations in the hull structure, induced by the propeller operation or unsteady flow such as vortex shedding; (iii) Flow-noise, including resonant excitation of cavities, plates and appendages. At the level of complexity suitable for the noise modelling considered here, see the discussion in section 2.2, it is however rational to focus on cavitation noise. In the review of noise models in chapter 3, a number of models are included which provides a broad-band estimate of these secondary noise sources. In particular the contribution from the main propulsion machinery, which is important at low speeds.
As is clear from the above discussion, any ship source spectrum contains line components (at harmonics of blade-rate tonals, hull vibrational frequencies and frequencies associated with the machinery) and a continuous, broad-band contribution.

2.2 Requirements and restrictions on the source model

The overall objective of the noise source modelling considered here, is to develop software tools for the prediction of the ambient noise from shipping, suitable for the Baltic Sea environment. Input data consists of information concerning the number of ships, and their location and operation during a certain time period. This input data can either come from monitoring of real traffic, or from the creation of scenarios, for which the environmental noise impact is to be studied. The four main component for such studies are: (i) Information concerning marine traffic, typically from AIS; (ii) Ship noise source modelling; (iii) Sound propagation modelling in the sea environment, and (iv) Noise effects and impact on fish and marine mammals.

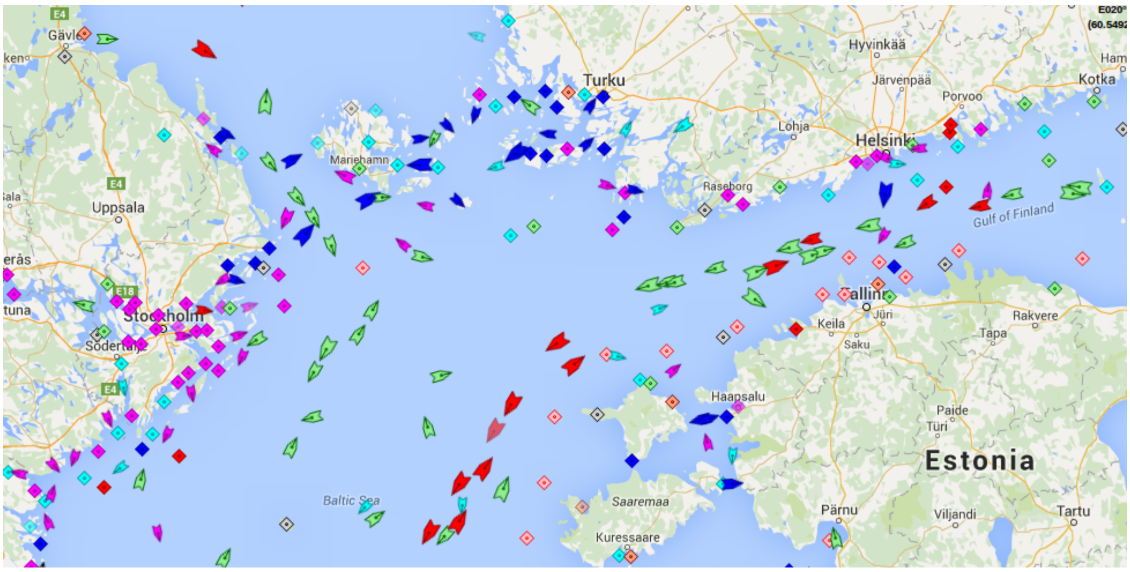

Figure 2.2: Screenshot from the openly available site `marinetraffic.com`. Display of current marine traffic based on AIS data. The ship symbol colours indicates ship type: Passenger vessels (blue), cargo vessels (green), tankers (red), etc.

In the SHEBA-project, all of these components are considered to some extent. It is planned to implement a noise source model in the AIS-data based software STEAM, [12], used and developed at FMI[1]. Then source maps, establishing noise source density per area, will be produced. This will allow for an impact assessment of ship generated noise. The source density will be compared year by year, and trends can be recognized. Additional validation data, based on existing measurements (from the BIAS, SONIC and AQUO projects) will be investigated in the project to validate, and possibly improve, the noise source modelling. Sound propagation modelling will be demonstrated for one or more relatively small areas, in Task 4.6 led by FOI[2]. Noise effects and impact on fish and marine mammals will be investigated in Task 4.7 led by SYKE[3].
A requirement on the noise model is that its parameters must be possible to determine from AIS-data, and from additional ship databases such as IHS-Fairplay and classification society databases. This requirement is also a restriction, as the model must be used for ship classes, and not individual ships. This fact also excludes any consideration of line contributions to the spectrum, which depend on the specifics of the actual ship. Hence, the noise spectrum should be represented in the broadband sense by the model. Source directivity is an aspect that may be taken into consideration in future developments. The standard, as is clear from the review in the next chapter, is however a directionally uniform radiation pattern, and this is also what is recommended here for the SHEBA-project. Finally, it is recommended that the source is formulated as a monopole, to be used as input to the creation of noise source maps and sound propagation modelling. Sometimes in the literature, noise sources are reported in terms of dipole levels, taking into account the acoustic reflection in the surface ("Lloyds' mirror effect"), [19]. This not so common however, so in the present report, source level is used exclusively to mean monopole source level.

[1]Finnish Meteorological Institute (FMI)
[2]Swedish Defence Research Agency (FOI)
[3]Finnish Environment Institute (SYKE)

3

A review of models for radiated noise

A review is provided of ship noise source models which fit the framework and requirements outlined in chapter 2. Historically, the most widely used such source models were proposed by Ross, [17]. To a large extent, this development was based on the first large data bases of ship noise measurements registered around WW2, [10, 17]. Furthermore, in the model development, the main noise generation mechanisms, and their scaling, was taken into account. A number of different parametrizations were proposed by Ross, in section 3.1 we give a description of one commonly used, which employs the ship speed and displacement. The RANDI[1] model, described in section 3.2, represents an adaption, or further development, of the models proposed by Ross. This adaption is based on noise data which (to the knowledge of the authors of this report) is not publicly available.

A different approach is represented by the development of the model proposed by Wales and Heitmeyer [20], which is described in section 3.3. This model is constructed by statistical analysis of 54 source spectra over the frequency band from 30 Hz to 1 200 Hz. Advantages of this model are that it is based on the most comprehensive recent data set, and that the statistical procedure for model determination is clearly described in [20]. This type of model is referred to as an *ensemble* source spectrum model, to indicate that it is determined by statistical analysis of an ensemble of ships of the appropriate type. In the present case this means a range of merchant ships.

In the first phase of the SONIC-project, a review was conducted of ship noise source models, [3]. This study proposes a model employing the Wales-Heitmeyer base spectrum, together with an amplitude scaling based on the Ross model, and a scaling constant tuned by the validation cases considered. This model is described here in section 3.4. It should be noted that this model was explicitly suggested as an intermediate model, to be evaluated, and possibly modified, during the SONIC-project. For this reason, the final recommendations of the SONIC-project (not available at the time of writing of this report) may suggest a modifications to the model. If that is the case, then this will also be considered in the further work in the SHEBA-project.

The last model to be included in this review was proposed recently by Wittekind [21], and is described in section 3.5. This model is particularly interesting since it explicitly models different contributions to the radiated noise, and one of them is noise

[1]RANDI = Research Ambient Noise DIrectionality, [7].

associated with the engine, which is important at low ship speed. Drawbacks of the model are that the modelling of the engine noise contribution is not based on openly available noise data [21], and that this model requires several additional parameters, as compared to the other models included in this review.
In the sections describing the models, care is taken to provide complete specifications of the models. Thus, the descriptions are self-contained for the model implementation work planned during the SHEBA-project. For in-depth discussion of the methodology used to construct the models, determine model coefficients etc., we refer to the original publications [17, 7, 20, 9, 21]. The definitions of the acoustic quantities used in the model descriptions, are collected in appendix A.

3.1 The historical Ross model

The historical Ross model [17] represents the source spectrum level $S(f)$, where f is the frequency, as a baseline spectrum S_0, together with a ship-dependent shifting (or scaling) of that spectrum S' which is determined by logarithms of the ship parameters,

$$S(f) = S_0(f) + S'. \tag{3.1}$$

The primary basis for this model development is the extensive measurement data from WW2, summarized in the report [10]. Analysis of the basic noise source generation mechanisms, primarily propeller cavitation, were also taken into account in the model development. The base spectrum has the simple form,

$$S_0(f) = 20 - 20\log_{10} f. \tag{3.2}$$

It is remarked, [17], that this expression is reasonable for ships at service speed, and for frequencies above 100 Hz. For lower frequencies there is more variation in the measured spectra.
In chapter 8 of the book by Ross [17], four different expressions for S' are suggested. Different ship parameters are required in the different expressions. The parameters are ship speed, displacement, propeller blade tip speed, and number of blades. For the purpose of comparisons in the present report, we use the expression,

$$S' = 134 + 60\log_{10}\frac{V}{V_{ref}} + 9\log_{10} D_T, \tag{3.3}$$

where the reference speed is, $V_{ref} = 10$ knots, and D_T is the displacement in tons. The expression (3.3) may be the most widely used among those suggested in [17].
In conclusion then, when reference to the Ross model is made in the present report, the following source spectrum model is used.

$$S_{Ro}(f) = 154 - 20\log_{10} f + 60\log_{10}\frac{V}{V_{ref}} + 9\log_{10} D_T \tag{3.4}$$

3.2 The RANDI model

RANDI is an abbreviation for "Research Ambient Noise DIrectionality", and it is a model for the prediction of ambient noise levels and directionalities, [7]. RANDI contains a ship source spectrum model which is an adaption, or further development, of the Ross models described above. In this section, the RANDI source spectrum model given. The presentation is an adaption of section 2 in the original report, [7]. The ship parameters used in the model are the ship speed and the ship length. The spectrum consists of three terms,

$$S_{RA}(f) = S_0(f) + S'(V, L) + S''(f, L). \tag{3.5}$$

Here S_0 is the RANDI base spectrum, and S' is the scaling based on ship parameters. Note that S_0 and S' in this section are different from the base spectrum and scaling in other sections. The third term, S'', is a relatively small correction term which is only non-zero for low frequencies (approximately below 200 Hz). The base spectrum is given by:

$$S_0(f) = \begin{cases} -10\log_{10}\left(10^{F_1(f)} + 10^{F_2(f)}\right) & \text{for } f < 500\text{Hz} \\ F_3(f) & \text{for } f \geq 500\text{Hz} \end{cases} \tag{3.6}$$

Here, $F_i(f) = \alpha_i + \beta_i \log_{10} f$, and the coefficient values are given in table 3.1.

Table 3.1: Coefficient values in the base spectrum of the RANDI model, [7].

i	α_i	β_i
1	-14.340	-1.06
2	-21.425	3.32
3	173.20	-18.0

The scaling function of the spectrum is given by,

$$S'(V, L) = 60\log_{10}\left(\frac{V}{V_{ref}}\right) + 20\log_{10}\left(\frac{L}{L_{ref}}\right) + 3, \tag{3.7}$$

where the reference speed is, $V_{ref} = 12$ knots, and the reference ship length is, $L_{ref} = 300$ feet. Finally, the third component of the RANDI model, the low-frequency correction term, is given by,

$$S''(f, L) = \gamma(f)\frac{L^{1.15}}{3643}, \tag{3.8}$$

where γ is a continuous low-frequency weighting function given by:

$$\gamma(f) = \begin{cases} 8.1 & \text{for } f < f_{c1} \\ 22.3 - 9.77\log_{10} f & \text{for } f_{c1} \leq f < f_{c2} \\ 0 & \text{for } f \geq f_{c2} \end{cases}$$

The frequency interval limits are, $f_{c1} = 28.4$ Hz, and $f_{c2} = 191.6$ Hz, respectively. This completes the description of the RANDI source spectrum level model.

3.3 The Wales-Heitmeyer model

The Wales-Heitmeyer model, [20], represents a different approach as compared with Ross and RANDI. The model is based on statistical analysis of noise measurements for a large number of merchant ships in transit. We refer to the original paper, [20], for a discussion of model formulation and procedure for determination of coefficient values. The end result is the following simple ensemble model for ship noise source spectrum, which has been fitted to a comprehensive recent data set of merchant ship noise data, [20].

$$S_{WH}(f) = 230.0 - 10\log_{10}\left(f^{3.594}\right) + 10\log_{10}\left[\left(1 + \frac{f^2}{340^2}\right)^{0.917}\right] \tag{3.9}$$

Only data above 30 Hz is used in the statistical analysis employed to determine the model coefficients, [20]. For this reason, we propose that a constant level is used below this frequency, i.e., $S_{WH}(f) = S_{WH}(30Hz)$, for $f < 30$ Hz.

3.4 The SONIC model

The SONIC model, as proposed in [9], consists of the Wales-Heitmeyer ensemble spectrum model as base spectrum, and a velocity-based scaling following Ross (see above).

$$S'_{SO}(f, V) = S_{WH}(f) + 60\log_{10}\left(\frac{V}{V_{ref}}\right) \tag{3.10}$$

In addition to this, a relatively elaborate procedure is proposed to determine reference/service ship speed, V_{ref}, for ship classes, based on AIS-data, [9]. As will be discussed in chapter 4, for certain ship classes, the ship length is taken into account when determining V_{ref}. Because of this, S_{SO}, implicitly depends on ship classification and (sometimes) ship length, through V_{ref}.
When validating (3.10) with data from the literature, a systematic underestimation of the radiated noise was observed, [9]. This motivated the inclusion of a constant off-set of 8 dB, leading to the following source spectrum, which we in this report refer to as the SONIC model.

$$S_{SO}(f, V) = S_{WH}(f) + 60\log_{10}\left(\frac{V}{V_{ref}}\right) + 8 \tag{3.11}$$

3.5 The Wittekind model

This recently published model, [21], differs from the models described above in that it consists of three separate contributions to the source spectrum level, and that it requires a larger number of ship parameters. For this model, the expressions are given for the source 1/3-octave band levels (instead of for the source spectrum level, as in the previous sections):

$$SL(f_k) = 10\log_{10}\left(10^{SL_1(f_k)/10} + 10^{SL_2(f_k)/10} + 10^{SL_3(f_k)/10}\right) \tag{3.12}$$

Here f_k is the center frequency for the k:th frequency band. We make the standard selection of center frequencies, with one at 10 Hz, and then the rest can be obtained by the 1/3-octave ratio, $f_{k+1} = 2^{1/3} f_k$, The first contribution, $SL_1(f_k)$, represents the low-frequency cavitation noise, $SL_2(f_k)$ represents the high-frequency cavitation noise, and $SL_3(f_k)$ the diesel engine noise.
The expression for SL_1 is obtained by a curve fit to data from Arveson and Vendittis (2008), [4], and leads to the following expression.

$$SL_1 = \sum_{n=0}^{5} c_n f^n + A(V, V_c, c_B) + B(D_T) \tag{3.13}$$

Here V_c is the cavitation-inception speed, c_B is the ship hull block coefficient, and the coefficient values c_i are given in table 3.2. The last two terms in the expression (3.13) model the scaling with speed and displacement respectively, and are given by the following expressions.

$$\begin{aligned} A &= 80 \log_{10} \left(\frac{4 c_B V}{V_c} \right) \\ B &= \frac{20}{3} \log_{10} \frac{D_T}{D_{T,ref}} \end{aligned}$$

Here, $D_{T,ref} = 10\,000\,\mathrm{t}$, is a reference displacement. The expression for SL_1 is only intended for relatively low frequencies, say below 400 Hz. The expression contains a fifth order polynomial in f and cannot be used for extrapolation to higher frequencies, where the other two contributions, SL_2 and SL_3 are dominant.

Table 3.2: Coefficients in the expression for SL_1 in the Wittekind model.

Coefficient	c_0	c_1	c_2	c_3	c_4	c_5
Value	125	0.35	$-8 \cdot 10^{-3}$	$6 \cdot 10^{-5}$	$-2 \cdot 10^{-7}$	$2.2 \cdot 10^{-10}$

For the high-frequency cavitation noise, SL_2, again a curve fit to exprimental data is used, [21], to obtain the expression,

$$SL_2 = -5 \ln f - \frac{1000}{f} + 10 + B(D_T) + C(V, V_c, c_B).$$

The function B models displacement effect, and is given above in connection with SL_1. The function C models speed influence (similarily as A, see above) and is given by,

$$C(V, V_c, c_B) = 60 \log_{10} \left(\frac{1000 c_B V}{V_c} \right)$$

Finally, for the engine noise SL_3, the following expression is given by Wittekind, [21].

$$SL_3 = 10^{-7} f^2 - 0.01 f + 140 + D(m, n) + E$$

Here D is a factor modelling the influence of engine mass and number of engines according to,

$$D = 15 \log_{10} m + 10 \log_{10} n,$$

where m is the engine mass in tons, and n is the number of (operating) engines. The last term, E, is a parameter describing the mounting of the engine with, $E = 0$, corresponding to an engine "resiliently mounted" and, $E = 15$, corresponding to an engine "rigidly mounted".

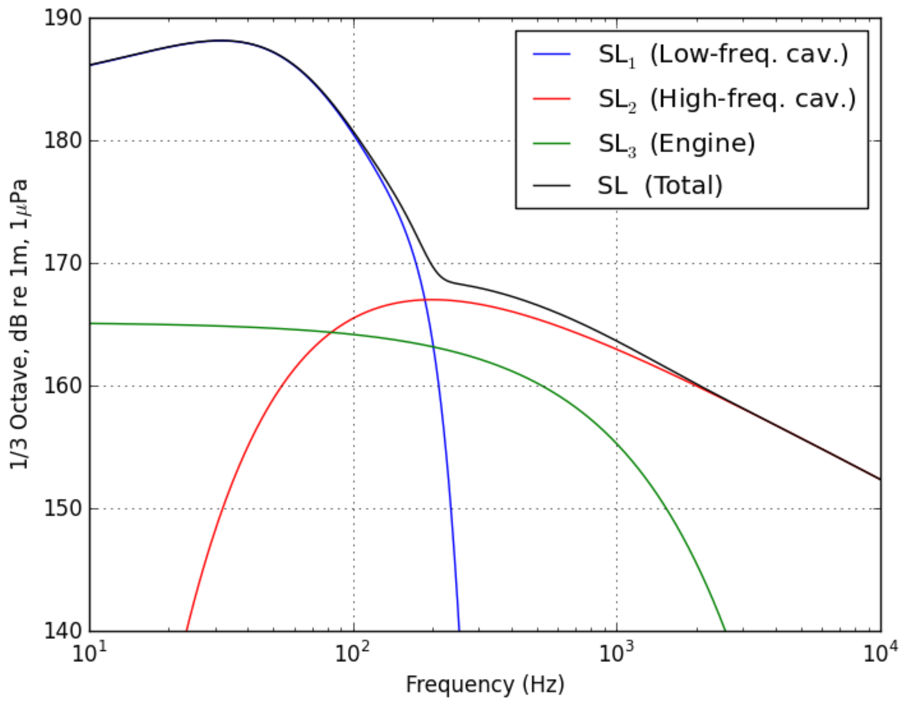

Figure 3.1: Source 1/3 Octave band level at ship speed 14 knots, calculated with the Wittekind model, for a ship with 33 000 t displacement, $c_B = 0.78$, $V_c = 9$ kn, and two diesel engines of 30 t. The engine mounting parameter is, $E = 0$. The three contributions are also shown in the graph.

In summary, this model depends on the following seven parameters; (i) The ship speed V; (ii) The cavitation inception speed V_c; (iii) The block coefficient c_B; (iv) The displacement D_T; and three parameters modelling the engine noise contribution; (v) Engine mass m; (vi) Number of engines n; (vii) A measure of how rigidly the engines are mounted E. In figure 3.1, the prediction of the model, and the three separate contributions, are illustrated using parameters typical for a bulk carrier. Figure 3.1 is a reproduction of figure 5 in the original paper by Wittekind [4].

3.6 Recommendations for the SHEBA project

In the SHEBA-project one or more ship source spectrum models are to be implemented in the STEAM software, [12], used and developed at FMI. A number of remarks and recommendations in relation to this planned work are collected here.
It is proposed that the SONIC model is used as a baseline for the developments. The base spectrum of the SONIC model (i.e. the Wales Heitmeyer model) is based on the

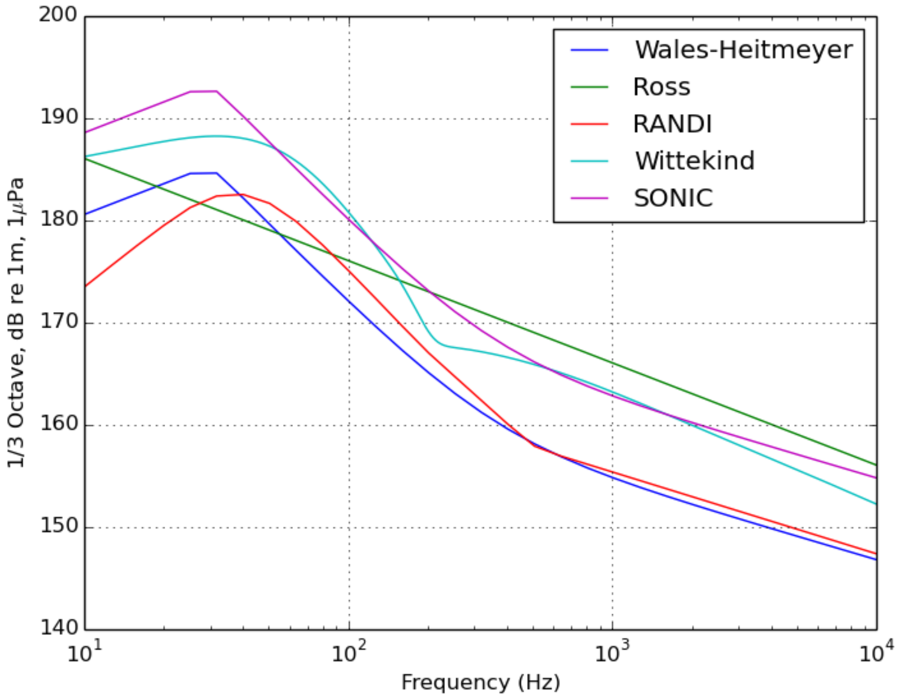

Figure 3.2: Comparison of the 1/3 Octave band source levels of the described models for a bulk carrier at 14 knots, with the following parameter values: $L = 173\,\mathrm{m}$, $D_T = 25\,515\,\mathrm{t}$, $c_B = 0.8$, $V_c = 9\,\mathrm{kn}$, $V_{ref} = 14\,\mathrm{kn}$, $m = 30\,\mathrm{t}$, $n = 1$, $E = 0$.

most comprehensive recent dataset available. In addition to this, the SONIC model has been developed for a purpose very similar to the objectives in SHEBA. Furthermore, an elaborate procedure to determine the model parameter (V_{ref}), based on AIS-data, has been developed for the most important ship classes, see chapter 4. This procedure includes estimates of the range of validity (at low speed) of the model. The suitability of other models can be further investigated during the SHEBA project. The Wittekind model is a candidate of particular interest here because of its potential for good prediction of engine noise, see the discussion on validation in chapter 5.

A restriction on the SONIC model was that parameter determination should be made strictly based on AIS-data. Within SHEBA, the possiblity to use additional information, from commercial information sources such as IHS-Fairplay, should be investigated. It may be possible to simplify (and make more accurate) the model parameter calculation. Also, the possiblity to use models depending on more parameters (not only V_{ref}), taking into account additional information, should be considered.

During the model implementation stage in SHEBA it is important to take into account the final evaluations and recommendations of the SONIC and AQUO projects, which is expected to be available in the during the fall 2015. Furthermore, noise measurement data from the BIAS project, and that produced within SHEBA, should be considered and may lead to modifications of the implemented ship noise source modelling.

4

Ship classification and determination of model parameters

Time-resolved information about the marine traffic provides input data for the noise source models described in chapter 3. The position and operating speed, and a number of ship parameters, are available in AIS. All noise model parameters are however not directly available, therefore a procedure for their calculation is necessary. An in-depth and updated review of AIS-parameters, together with assessment of reliability is give in [9]. In addition to this, a comprehensive procedure for model parameter determination for the SONIC-model has been elaborated, [9], see figure 4.1 for an illustration of the top level ship classification employed. For the purpose of the SHEBA-project, additional sources of information should be considered, such as the commercial IHS-Fairplay.

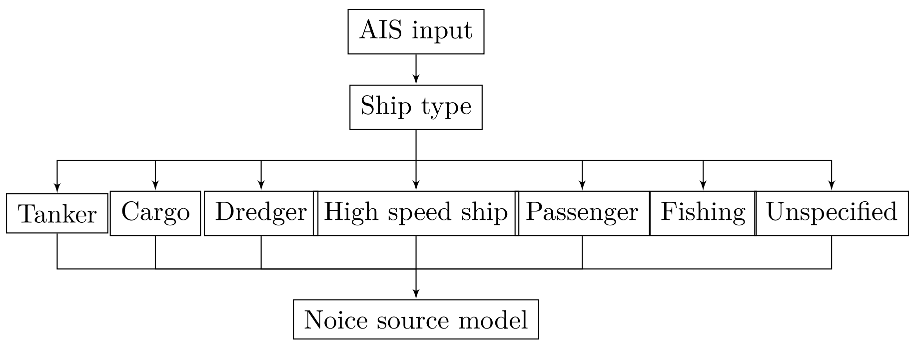

Figure 4.1: Illustration of the top level of the ship classification scheme proposed in SONIC, [9]. For each ship category, the determination of the model parameter, V_{ref}, is carried out in a specialized manner.

There are no universally accepted definitions for ship type, and various sources use different definitions. See table 3 in [9] for a comparison of the classifications used by AIS, IMO, DNV class notation, and "Significant Ships" respectively. In table 4.1 the most important classes are listed according to the classification scheme of [9] (based on AIS). The models described in chapter 3 need between zero and seven input parameters, and the total list of parameters is: (i) Speed V; (ii) Displacement D_T; (iii) Length L; (iv) SONIC-model reference speed, V_{ref}; (v) Cavitation inception speed, V_c; (vi) Block coefficient, c_B; and (vii) The three engine parameters of the Wittekind model, m, n and E.
If additional data sources are used (not only AIS), this may lead to two benefits as compared to the solution in the SONIC-project. First, within the baseline SONIC-

model, the parameter determination may be achieved simpler and more accurately. Second, this opens the possibility to consider the implementation of an additional model, which was excluded from SONIC because of unavailability of parameter information. A most important next step within SHEBA is to investigate these aspects.

This chapter is concluded with a number of remarks concerning parameter determination, noise characteristics, and noise model validity, classified according to ship class, for the most important noise contributions. As is further discussed in chapters 2 and 5, the noise source models are most suited for large ships at service speed (typically in transit) when the propeller caviation is the dominant noise source. Based on AIS-data, it is estimated that the categories tankers, cargo ships and passenger ships account for the dominating part of the ship noise, in the open sea, in the Baltic.

Tankers - One special feature of the Baltic Sea is that there are essentially no very large tankers operating there. In this respect, the SHEBA-perspective is different from that considered for instance in the SONIC- and AQUO-project. In Annex 2 in [9], a relatively complicated procedure is described to estimate the SONIC reference speed for tankers. It relies on a relationship between speed and deadweight tonnage (DWT). For most ships (DWT >10 000 t), it leads to a reference speed of approximately 14-15 knots.

Cargo ships - This category includes bulk carriers, container ships, RoRo ships and other types of cargo ships. Most data sources include a large sub-category called “General Cargo”. Generally, there is a quite large variation in service speed within the category of cargo ships. One weakness of the SONIC-model, pointed out in [9], is that AIS-data is lacking in detail for cargo ships. The suggested approach was to subdivide this category (identifying container ships) based on operating speed. The shortcomings of this are however evident. With additional data sources, it is clearly possible to improve the source modelling for this category.

Passenger ships - The most important (from a noise perspective) classes here are cruise ships and RoPax ships. There is a possible overlap of this category, with the category “High speed ships” in a number of data sources. In [9], the reference speed, $V_{ref} = 22\,\mathrm{kn}$, was suggested uniformly for large passenger ships, including both ferries and cruise ships.

Miscellaneous - The noise characteristics of the remaining ship categories naturally represent a very varied set of sources. Here we only collect a number of brief remarks which may be of importance during the SHEBA-project. High-speed craft, typically large fast ferries (frequently catamaran) and small offshore service vessels, may be important noise sources. If this is the case, special noise source modelling and validation should be considered for this category. For fishing vessels, the uniform reference speed 10 knots was proposed in [9]. Two ship types, which may need to be considered, and for which specialized noise source modelling would be necessary, are dredgers [9, 16], and ice-breakers [18]. Small leisure boats have been shown to radiate significant noise at high frequencies, [13]. Near densely populated areas it may be critical to include small leisure boats, and in that case develop a specialized noise model.

5
Model validation

The chapter contains a discussion of noise source model validation, illustrated by a number of examples from the literature for measurement data [4, 13, 9]. In table 5.1, the ship parameters for the validation cases presented in this chapter are summarized.

Table 5.1: Ship parameters for the cases included in the validation plots. The listed operating speeds V, are used in different plots. The reference speed V_{ref} is determined for the SONIC model. Reference is given to the publication with the measurement data. A dash at an entry means that it is not known, and not needed for the result plots. The ships are: #1 M/V Overseas Harriette; #2 Crystal Harmony; #3 Statendam; #4 Norwegian Wind; #5 Norwegian Sky.

	Ship#1	Ship#2	Ship#3	Ship#4	Ship#5
V(kn)	8, 10, 12, 14	10.5, 15.3	10.8, 18.0	10.0, 19.2	10.8, 14.2
V_{ref}(kn)	14.0	22.0	22.0	22.0	22.0
L(m)	173	241	219	230	260
D_T(t)	25 515	49 000	55 000	50 000	77 000
c_B	0.8	-	-	-	-
m(t)	30	-	-	-	-
n	1	-	-	-	-
E	0	-	-	-	-
Reference	[4]	[13]	[13]	[13]	[13]

The models reviewed in chapter 3 were developed and tuned using two types of data sets. The Ross, RANDI and Wittekind models rely on large noise databases which are, to some extent, not publicly available due to commercial or military constraints. The Wales-Heitmeyer model and the SONIC model have the advantage that they were developed and tuned based on noise data which is openly available to the research community. As pointed out in [9], there are a number of shortcomings in the limited amount of published material on ship noise measurements which significantly limits model validation. These include; (i) Varying methodologies used during full-scale trials; (ii) Various data processing methods are used; (iii) Variable detail regarding the measurement methodology and ship parameters and operating conditions.

The significant efforts in the projects BIAS, SONIC and AQUO will likely lead to new validation data which then will be considered during the SHEBA project. Also, within the SHEBA-project, further measurements will be considered in connection with noise source model implementation. Particular sources that will be taken into account include the concluding recommendations the SONIC- and AQUO-project, expected during the fall 2015, and data in the SONIC-database [8].

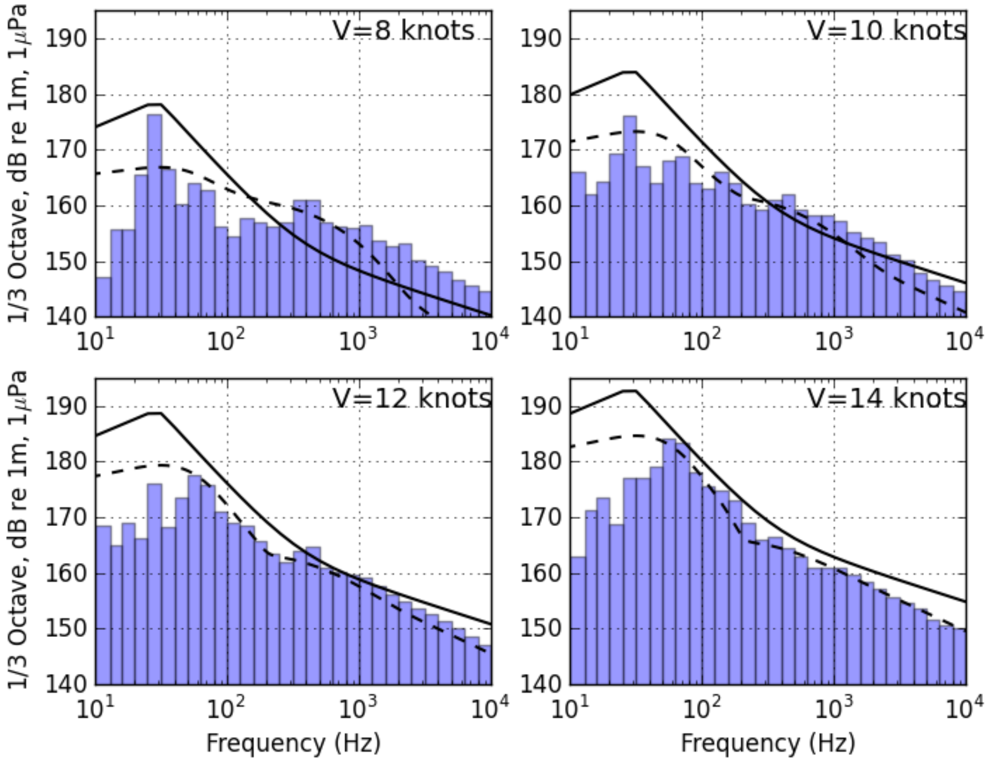

Figure 5.1: Validation for Ship #1, M/V Overseas Harriette. Source 1/3 Octave band levels are presented at four different ship speeds. Noise measurements, [4], are plotted using bars, and the full line indicate predictions using the SONIC model, and the dashed line indicate predictions of the Wittekind model.

Two validations cases are next briefly discussed, the main purpose being to illustrate the validation process. For an in-depth discussion of model validation, we refer to [9] and the references therein. Both cases are very good with respect to: (i) Acoustic measurement equipment employed; (ii) Measurement location with low levels of background noise; (iii) Detailed descriptions of set-up of measurements and data processing procedures; (iv) Several runs measured for each ship; (v) Extensive information available about ship parameters and operating conditions.
The measurements of the first validation case, the bulk cargo ship M/V Overseas Harriette (see table 5.1), were reported in [4]. A range of speeds were measured, and the results from four of them are shown in figure 5.1. Also included in the results plots for comparison are predictions from the SONIC and Wittekind models. The model parameters for the diesel engine contribution in Wittekind-model were not available in [4], so generic values had to be used. The noise model parameters are summarized in table 5.1. This case was one of the validation cases used for the SONIC model, see [9], in particular figures 7, 8 and 15. The largest discrepancy between models and measurements is seen at the very low frequencies, below 50 Hz.

This is however caused by the Lloyd' mirror effect, for which the measurement data is not corrected (hence reporting dipole levels, see the discussion in chapter 2). For the higher speeds, 10 knots and faster, the SONIC model differs less than 5 dB, for frequencies above ≈ 80 Hz. It is noted that this ship and operating condition, with significant cavitation noise, is representative of the cases for which the model was developed. The Wittekind model show a remarkably good agreement with data, at least for 10 knots and faster. It is however not possible to draw general conclusions from this, since this is only one single ship comparison, and some of the model parameters had to be given rough estimates.

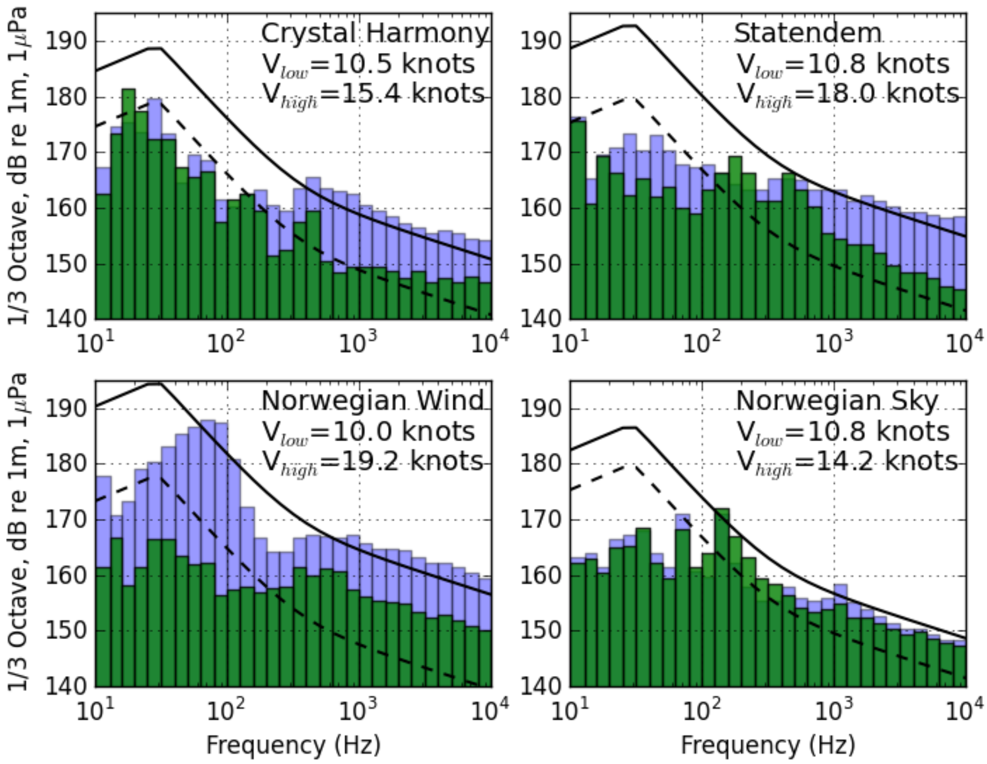

Figure 5.2: Validation for cruise ships, Ship #2-5, see table 5.1. Source 1/3 octave band levels are presented at two speeds for the four different ships. Note that the two speeds tested for each ship are different (and indicated in the graphs). Noise measurements, [13], are plotted using green bars for the low speed and blue bars for the high speed. Full lines show predictions of the SONIC model at the high speed, and dashed lines show the predictions of the SONIC model at the low speed.

The second validation case, shown in figure 5.2, includes four cruise ships, and is based on measurements reported in [13]. Two speeds were measured for each ship (different speeds for different ships). This case is more difficult, since the measured speeds were lower relative to the design speed of the vessels. For this reason, the relative contribution from the cavitation noise was smaller, and there were often large contributions from the machinery. In the resuls plots, only predictions by the SONIC model was included, since information about model parameters for the Wittekind was not available. This case is also used for validation in the SONIC-project, see figure 11 of [9]. The validation case clearly illustrate the difficulties involved in modelling the machinery contribution to the radiated noise, and we refer to [13, 9] for several important observations concerning the similarities and differences of the ship source spectra measured, and how they are related to cavitation and machinery contributions.

6
Summary

Noise source modelling methodology suitable for application to Baltic Sea shipping has been reviewed. The material is focused on ship source spectrum modelling, and how to determine model parameters from AIS-data, and additional data sources. The relation to noise measurements, sound propagation modelling and effect and impact on fish and marine mammals was also discussed, in section 2.2.

The suitable class of ship source spectrum models is identified to be a monopole source, providing the broad band spectrum of the source, but not including directional noise radiation. A review of models within this class is provided in chapter 3, and five widely used models are described in detail. Care is taken to provide complete specifications of the models, with sufficient level of detail for their implementation. The SONIC-model, see section 3.4, is proposed as a baseline model for the SHEBA-project. Arguments supporting this are discussed in section 3.6. Furthermore, it is recommended that additional models are considered for use. In particular the Wittekind-model, see section 3.5, may be appropriate for the low-speed range since it separately models the machinery noise, which becomes important when the propeller cavitation noise is no longer dominant. During the model implementation stage in SHEBA, it is important to take into account the final recommendations of the SONIC and AQUO projects (expected during the fall 2015), as well as noise measurements from the BIAS and SHEBA projects.

It is most important in the planned model implementation stage of SHEBA to consider the use of other data sources, in addition to AIS, such as the commercial IHS-Fairplay. As discussed in chapter 4, possible improvements include a simpified and more accurate way to determine the model parameters, and the possibility to employ models which require additional input parameters.

The type of noise source modelling considered here has mainly been designed for large commercial ships operating at design speed, when there is significant propeller cavitation. This is typical for the transit operating condition in the open sea. Reasonably accurate predictions are demonstrated for this case, see the validation studies in chapter 5. Validation studies also indicate that the speed power law of the SONIC-model is broadly valid above cavitation inception speed. It is however generally recognized that there is a need for improvement of publicly available databases of ship noise of high quality, and with well-documented measurement procedures, [14, 9].

Known issues with the established ship noise source modelling include: (i) Inaccuracy at low operational speed, of special importance near harbours, but also in connection with the practise of "slow steaming". (ii) Any classification based exclusively on AIS leads to inaccuracies in the model parameter determination due to lack of information, for instance concerning passenger ships, see chapter 4 and [9]. (iii) Validation for ships with controllable-pitch propellers indicates that the SONIC-model underestimates the radiated noise levels. (iii) It is not suitable for special classes of vessels, such as dredgers and small leisure boats. Definition of speciallized spectra may be appropriate for one or more of these classes.

A

Quantitative measures of sound and acoustic definitions

The definitions of the different quantitative measures of sound and source strength, which are used in the report, are defined in this appendix. An effort is also made throughout the report to be consistent with the terminology in order to avoid confusion and ambiguities which sometimes occurs in the literature on underwater acoustics.
In particular, the terms *source level* (equation A.1), *source spectrum level* (equation A.2) and *source 1/3-octave band level* (equation A.3) are defined below, and notation is introduced. An effort is made to follow established standards, and the material is adapted from standard references, [15, 17, 19].

A.1 Sound-pressure level and source level

The acoustic pressure $p(\mathbf{x}, t)$, generated by a source is considered. Here $\mathbf{x}$ denotes the spatial (vector) coordinate and t time. At a point in the far-field, the intensity, $I(\mathrm{W/m^2})$, is given by,

$$I = \frac{\sigma(p)^2}{\rho_0 c_0},$$

where $\sigma(p)$ denotes the standard deviation of the pressure at the point, ρ_0 denotes the density and c_0 the speed of sound. The most commonly used measure of sound is the **sound-pressure level** in decibels,

$$SPL = 20 \log_{10} \frac{\sigma(p)}{p_{ref}},$$

where the reference pressure is taken to be, $p_{ref} = 1\,\mu\mathrm{Pa}$, for water. To indicate the reference level explicitly, the sound-pressure level is written:

$$SPL[\text{dB re } 1\mu\text{Pa}]$$

Next, this is related to a corresponding measure of the source strength, or source level. For this purpose, we consider a point source with no directional dependence of the radiated sound. For spherical radiation, at a distance R from the source, the intensity is,

$$I = \frac{P}{4\pi R^2},$$

where P(W) is the power of the acoustic radiation of the source. The **source level** in decibels is now defined using the acoustic intensity at a reference distance of 1 m. Using the above expressions, it can be written in the following way, in term of the acoustic power of the noise source.

$$L_S[\text{dB re 1m, }1\mu\text{Pa}] = 10\log_{10}\frac{\rho_0 c_0 P}{4\pi p_{ref}^2} \tag{A.1}$$

A.2 Frequency dependence

The frequency dependence of the acoustic pressure generated by the source is considered in this section. Again, the starting point is to consider the acoustic pressure at a spatial location. In terms of its Fourier representation it is,

$$p(t) = \sum_{n=1}^{N} A_n \cos(2\pi f_n t - \theta_n).$$

Here the dependence on $\mathbf{x}$ is not explicitly written. For convenience, only the case of a discrete spectrum is treated here. The generalization to a spectrum with both discrete and continuous contributions is straight-forward. The corresponding complex expression is,

$$A_n \cos(2\pi f_n t - \theta_n) = \text{Re}\left\{\hat{p}_n e^{2\pi i f_n t}\right\},$$

which implies that,

$$\hat{p}_n = A_n e^{-i\theta_n}.$$

The standard deviation of the pressure signal can be expressed in terms of the Fourier coefficents as follows.

$$\sigma(p)^2 = \lim_{T\to\infty}\frac{1}{T}\int_{t_0}^{t_0+T} p^2(t)\,\mathrm{d}t = \frac{1}{2}\sum_{n=1}^{N}|\hat{p}_n|^2$$

Using this, the corresponding expressions for intensity and source strength can also be obtained in terms of the Fourier coefficients. The **spectral density** is now defined by,

$$q(f) = \frac{2}{\Delta f}\sum_{f_n\in F}|\hat{p}(f_n)|^2,$$

where F is a frequency interval of (small) length Δf, centered around f. The unit of spectral density is, Pa^2/Hz. The corresponding decibel expression is called the **sound-pressure spectrum level**, and is given by,

$$SPSL(f) = 10\log_{10}\frac{q(f)}{p_{ref}^2/\Delta f_{ref}},$$

here Δf_{ref} is a reference frequency interval which, by convention, is taken to be, $\Delta f_{ref} = 1\,\text{Hz}$.

Analogously as for the source level in the preceeding section, by considering the case of spherical radiation and normalizing to a reference distance of 1 m, the **source spectrum level** is obtained,

$$S(f)[\text{dB re 1m, }1\mu\text{Pa}^2/\text{Hz}]. \tag{A.2}$$

Often the source spectrum is given in 1/3-octave bands. In terms of the source spectrum level, the 1/3-octave band level can be obtained by first converting from decibels, then integrating over the frequency band, and finally converting back to decibels. The resulting **source 1/3-octave band level** is given by,

$$SL(f_k)[\text{1/3 Octave dB re 1m, }1\mu\text{Pa}] = 10\log_{10}\int_{f_{k,l}}^{f_{k,u}} 10^{S(f)/10}\,\mathrm{d}f. \tag{A.3}$$

Here f_k is the center frequency of the k:th 1/3-octave band, $f_{k,l}$ is the lower frequency limit of this band, and $f_{k,u}$ is the upper frequency limit. In the present report, the standard 1/3-octave center frequencies are used, with one at 10 Hz, and then the rest can be obtained by the 1/3-octave ratio, $f_{k+1} = 2^{1/3} f_k$, see e.g. table 2-1 in [15] for a listing of the resulting frequencies.

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