A prediction method for the underwater acoustic signature of steel surface vessels, allowing for a quick approximation during the design stage

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This paper describes a prediction method for the contribution of the main onboard machinery to the underwater acoustic signature of steel surface vessels that can be used during the design stage.
There are two reasons for the development of this method. Firstly, a small acoustic signature is important for naval and research vessels, due to operational requirements concerning detection and interference with acoustic equipment. Furthermore, anthropogenic noise underwater is an issue that receives increasing attention from the international community. This is due to the increase of underwater ambient sound levels over the last decades and concerns about the impact on marine life.
The method uses Statistical Energy Analysis to model the vibration levels on the hull, using a simplified representation of the vessel. These levels are converted into the source level of the vessel using the radiation efficiency.
The method is validated with measurements. The simplification of the vessel is shown to perform well, compared to a complete model for the underwater acoustic signature. The output of the method shows resemblance to measurement values for frequencies of 200 Hz and up, but further validation is necessary to incorporate the method in the design process.

This paper is based on a thesis written for the master Marine Technology at Delft University of Technology. It was written under the supervision of Tjakko Keizer at Damen Shipyards Gorinchem. For more information: Tjakko.Keizer@damen.com

Introduction

The need to limit the underwater acoustic signature of a vessel is apparent for research vessels and naval vessels, because of their operational requirements. While research vessels suffer from interference with their equipment or subject of research, naval vessels aim to minimize the chance of detection. Besides the operational aspects, underwater radiated sound is an important issue due to environmental concerns. The subject gained attentions since the end of the twentieth century. Multiple indications were found that the underwater ambient noise had increased significantly as a result of an increase in size, horsepower and intensity of shipping and other human activities in the ocean. [27] Several different reports have been written about the increase of the underwater ambient sound level, but it is difficult to draw generic conclusions, since measurement data is scarce. In general, claims are done for locations with high intensity shipping of an increase in ambient sound levels of at least 3 decibel per decade. [2]

Little is known about the impact of this increase on marine life can be drawn, because this is difficult to record and analyze. What is known, is that sound is an important means for creatures in the ocean: sight is limited and in water sound propagates over large distances with little attenuation. Sound is used by marine animals for a range of applications including echo-location and communication. [25] Therefore, the anthropogenic noise introduced in the ocean can be expected to have consequences.

The International Maritime Organization has responded with guidelines in an attempt to streamline research efforts and Det Norske Veritas and Bureau Veritas have both come up with classification for underwater radiated sound. [19, 15, 8] Furthermore, the International Organization for Standardization issued guidelines for measurement of underwater radiated sound and several research projects have been initiated concerning the subject. [20, 3] Eventually requirements might be formulated for commercial vessels.

Damen builds both naval and research vessels and thus mainly due to the operational implications of the underwater radiated sound, but also to be prepared for the future, Damen wants to develop a prediction method for the underwater acoustic signature of its vessels. Therefore the goal of this work is:

To develop and validate a prediction method that can be implemented in the early design stage for the contribution of the main machinery to the underwater acoustic signature of steel surface vessels.

The underwater acoustic signature of a vessel can be attributed to three distinct sources: the propeller, the machinery and flow sound. In this case the scope is limited to the machinery contributions.

A modeling method had to be chosen for this prediction and different options have been investigated. Based on the comparison, the decision was taken to use Statistical Energy Analysis (SEA). This choice was motivated by the fact that SEA can be applied to any ship type, because it is no empirical method, and because it offers the opportunity to expand the model in a later stage to include more details. Its flexibility also allows for the systematic variation of several design options and to investigate the implications of design choices.

It is necessary to create a simplified model of the ship for application in SEA, since the prediction should be done in the early design stage and details of the design are unknown at that time.

In this paper several subjects are discussed in four parts: the theory, the model, the validation and the evaluation. In the theory, Statistical Energy Analysis, radiation, underwater sound and the term 'affected level' are introduced. Part II, the method, includes the approach, the design, the input and the components of the method. The validation consists of the validation of the onboard levels and the underwater levels. Finally, the evaluation contains the conclusions and recommendations.

List of symbols

ρ_0	density of the medium	[kg/m^3]
ω	angular frequency	[rad/s]
σ	radiation efficiency	[-]
c_0	sound speed in the medium	[m/s]
f	frequency	[Hz]
f_c	coincidence frequency	[Hz]
F	root mean square force	[N]
k_0	acoustic wave number	[rad/m]
k_b	bending wave number	[rad/m]
m	mass per unit area	[kg/m^2]
S	area of the structure	[m^2]
t	thickness of the plate	[m]
v	root mean square velocity	[m/s]

PART I - THEORY

Statistical Energy Analysis

SEA is a method that can be used to model the vibro-acoustic response of structures. It was developed in response to the FEM/BEM methods that were not able to yield high frequency results and that were very complex. SEA proved to be a useful tool to model high frequency response and is much simpler. [24]

In SEA the entire system is divided in subsystems and the interaction between these subsystems is based on one degree of freedom: energy. Energy can either be transferred to a subsystem from an external input or from another subsystem. The exchange between subsystems is governed by the coupling loss factor, which is determined by material and geometrical parameters. A unique coupling loss factor is the radiation loss factor, which determines the radiation into the surrounding media. Energy can also dissipate from a subsystem by damping.

The name of the method contains the word 'statistical' which means that the answers are based on a draw from a population with the same characteristics and are thus based on statistics. [23]

Simplified models in SEA

For this prediction a simplified model of the vessel is created, in order to satisfy two requirements:

- The prediction should be fast.
- The prediction should be done in the design stage and should thus be possible based on the limited information available at that stage.

A simplified representation of the vessel should work, because SEA is a program that functions best for simple models. A more detailed model is more sensitive to the introduction of small mistakes and inconsistencies, because more (possibly incorrect) information is supplied. Furthermore, the current model is intended for underwater sound, a more global phenomenon that is expressed in one overall level representing the entire vessel. This means that details of the structure should have negligible influence on the global parameter evaluated here.

SEA software

The SEA software that was used during this project is VA One, developed by the ESI group.

Radiation

Structural vibrations become audible if the vibrational energy is transformed into acoustic waves in a medium like air or water. [10] The vibrations in the structure set the surrounding medium in motion and thereby cause sound waves to propagate. The effectiveness of this transfer of energy is expressed as the radiation efficiency. The power radiated by a structure is governed by equation 1. [16]

$$\Pi_{rad} = \rho_0 c_0 S v^2 \sigma \quad \text{[watt]} \tag{1}$$

ρ_0 is the density of the medium [kg/m^3], c is the sound speed in the medium [m/s], S is the area of the structure [m^2], v is the root mean square velocity [m/s], and σ is the radiation efficiency [-].

The radiation efficiency is the ratio between the radiated acoustic power and the radiated acoustic power of a "uniformly vibrating baffled piston at a frequency for which the piston circumference greatly exceeds the acoustic wavelength." [17] The radiation efficiency can be larger than unity.

Different aspects of radiation come forward in the following paragraphs: the radiation regimes, the coincidence frequency, radiation below coincidence, fluid loading and radiation theories.

Radiation regimes

Different radiation regimes can be identified [6]:

- Radiation from global modes of the entire vessel.
- Radiation from plate modes.
- Radiation from a point force excitation.

The global modes are limited to low frequencies, for a ship of 150 meter to about 20 Hz, where the modes span the entire vessel. These modes have a negligible contribution to the underwater acoustic signature. The negative image source due to the reflections at the surface cancels the radiated sound. [29]

Radiation from a point force is not relevant in this case either, because the hull is not excited by a point force. Therefore, the further analysis focusses on plate modes.

Coincidence frequency

The coincidence frequency, or sometimes critical frequency, is an important parameter for the radiation from a plate. At this frequency the bending wave speed in the plate is equal to the sound speed in the medium. Since $\lambda = \frac{c}{f}$ this means that the wavelength in the plate and in the wavelength in the medium are also equal.

This equality can be achieved since the frequency is proportional to the wavelength in the plate with $\frac{1}{f^{(1/2)}}$ and in the surrounding medium this relation is equal to $\frac{1}{f}$. [17] Above the coincidence frequency the bending wave speed is lower than the sound speed in the medium and the bending wavelength is smaller than the wavelength of the acoustic waves.

For radiation in water for a steel plate, the coincidence frequency is given by equation 2. [11]

$$f_{c,water} \approx \frac{235}{t} \quad \text{[Hz]} \tag{2}$$

t is the thickness of the plate [m].

For radiatio into water coincidence is found at much higher frequencies than for raditiation into air, where the coincidence frequency for a steel plate is found by $f_{c,air} \approx \frac{12}{t}$. This yields the regime below coincidence much more important when water is concerned. Actually, the entire frequency range of interest lies below coincidence as hulls are generally about 0.01 m thick. Coincidence is then found at 23500 Hz for a steel structure. Therefore, radiation below coincidence is analyzed in the next paragraph.

Radiation below coincidence

In the case of an infinite plate, below coincidence no radiation is found. [28] A phenomenon occurs, called 'radiation cancellation' [17] or a 'hydrodynamic short circuit'. [10] The vibration of the plate translates into the medium setting particles into motion. The consequent propagation of the motion is with the speed of sound. When the plate vibrates, locations where the particles are compressed and rarefied, alternate. Particles are attracted to the rarefied regions and thus the motion that was caused by the plate vibrations is canceled. This cancellation is successful up to the point where the wave in the plate is faster than the propagation of the disturbance in the medium. From that point on the waves are not able to cancel out anymore and the disturbance propagates further away from the plate, radiating energy into the medium. The switch lies at the coincidence frequency. [17]

There is an edge to this, literally, as the short circuit is not complete in the case of a discontinuity in the plate. This can be an edge or a stiffener, for example. In the case of a discontinuity the rarefied and compressed regions do not alternate evenly and the disturbance propagates into the medium. For a structure radiating into the water, the frequency range of interest lies below the coincidence frequency. Radiation therefore comes from edges and discontinuities.

Fluid loading

When radiation into water is concerned another phenomenon is also important: fluid loading. Fluid loading has three distinct effects [22, 18]:

1. It mass-loads the structure, influencing the vibratory motions. The effect is that the wave number and thus the natural frequencies shift.
2. It increases radiation damping, thus reducing the radiation efficiency.
3. It enables the existence of coupling terms between different partitions. This means the plate cannot be assumed to be set in a rigid baffle.

Fluid loading was shown to have a significant effect on the radiation. [21] Therefore, in the next paragraph radiation theories are looked at that account for fluid loading.

Radiation theories

In the previous paragraph it was established that fluid loading is of importance for radiation into water. Furthermore, it was established that for radiation into water the regime below coincidence is of interest. Theories are suitable for radiation into water are not abundant and rely mainly on research done by Davies [13, 12, 14], Berry [5] and Rumerman [30]. Recently, Cheng [9] introduced engineering formulas for radiation from submerged plates, based on the radiation efficiencies in air from Xie [33].

Rumerman draws the conclusion that generally the light fluid-loading yields radiation efficiencies that are too large for fluid loading conditions. His conclusions are confirmed by measurements. [21]

Rumerman approximates the radiation below coincidence by estimating the line forces that are exerted on the fluid. The line forces are the reaction forces needed to cancel the vibrations found in the structure at the boundaries, and can be approximated using the vibration velocity of the plate and line mobilities. Equation 3 [30] gives the power radiated per unit length of the line force.

Besides the general equation both asymptotic equations for $\mu >> 1$ (light fluid loading) and $\mu << 1$ (heavy fluid loading) are also given. μ is the fluid loading parameter defined by $\mu = \frac{m\omega}{\rho_0 c_0}$, m is the mass per unit area [kg/m^2], ω is the angular frequency [rad/s], ρ_0 is the density of the medium [kg/m^3] and c_0 is the sound speed in the medium [m/s].

$$\Pi = \begin{cases} \frac{F^2 \rho_0}{2\omega m^2}(1 - \frac{1}{\sqrt{1+\mu^2}}) & \text{all situations} \\ \frac{F^2 \rho_0}{2\omega m^2} & \mu >> 1 \\ \frac{F^2 \rho_0 \mu^2}{4\omega m^2} & \mu << 1 \end{cases} \tag{3}$$

F is the root mean square force [N] and m is the mass per unit area [kg/m^2]. The force can be determined from the velocity level and the mobility for a unit length of the boundary. The force represents the boundary in its entirety, so on both sides, and the length should only be included once. For the analysis of a collection of plates, this means that only half the perimeter should be taken into account, otherwise the boundaries are included twice.

Underwater sound

Expressing an underwater sound level in decibel is done with a reference level of 1 μPa, instead of the reference level of 20 μPa used for sound in air. This is done to ensure positive levels as sound pressure levels underwater are lower than above water. Underwater the experience of sound is different than in air, since the relation between pressure and intensity is different.

Sound propagation underwater differs from propagation in air. Sound travels more than four times faster underwater than above water and attenuation in water is significantly smaller. Furthermore, two large reflectors are found in the ocean: the surface and the bottom. The reflection at the surface is called the Lloyd mirror effect. The surface is assumed to act as a perfect mirror in the case of negligible waves, providing a negative mirror image source. The reflections at the bottom are more complex due to variation in composition and roughness of the bottom and give a positive image source.

In the presence of surface reflections, a negative mirror source, the radiated levels are cancelled partially at low frequencies and the levels are amplified up to 3 dB at high frequencies. For bottom reflections, a positive mirror source, in low frequencies amplification of up to 6 dB is found and for the high frequencies amplification of up to 3 dB is found. Often only surface reflections are important, because the water depth is large enough to yield the bottom reflections negligible.

At the moment the underwater acoustic signature of a vessel is determined with underwater acoustic measurements, generally at an acoustic range. Professional ranges consist of hydrophones at several depths and positions and are located in deep water to minimize the contribution of bottom reflections. The ship is regarded as a monopole source and the signature of the vessel is expressed as a level at one meter from the acoustical center. The acoustic center is the location of the monopole that represents the underwater acoustic signature in theory. The location of the acoustic center should be determined by the analyst of the data.

Generally dynamic measurements are done, this means that the ship sails past the hydrophones. The acoustic signature is measured for a specified data window length to take the contributions of the entire vessel into account, afterwards energetically averaging the results. Static measurements, where the vessel stays in one position, are also possible to determine the contribution of specific machinery.

To calculate from the receiver back towards the acoustic center of the vessel after underwater measurements the decrease in sound level due to geometrical spreading is important. This decrease is determined by the relation $20log_{10}(r)$, assuming spherical propagation. r indicates the distance to the source. [31]

Affected level

The final goal of the prediction is to express the underwater acoustic signature of the vessel as a source level. This concept was introduced to be able to express the underwater acoustic signature in a single value as a function of frequency. It is the representative level at 1 meter from the vessels acoustic center. The values are averaged there as if the vessel is a monopole that radiated sound from that point exclusively.

The source level is an artificial level, since the true level at the acoustic center will not be the same as the source level. Contributions of individual sources will be dominant and near-field effects are found. It is however useful to allow for comparison between vessels and to concisely express the underwater acoustic signature.

There is some discussion about whether it is correct to call the result of a measurement the 'source level' since the term implies that the value is completely independent of its environment and is a characteristic of the vessel alone. This is not true for the result of a measurement and therefore it should rather be called differently, a suggestion is the ' affected source level'. [7] In this paper the term 'affected level' is used.

The difference between the source level and the affected level was investigated to be able to better compare the model to the requirements. Factors that form a constant difference between the measurement and the model were looked at. These were: the surface reflections, post-processing and the location of the acoustic center were looked at. All three have their distinct influence on the measurement value.

The comparison between the source level and the affected level was made for a situation where the measurement was executed perfectly for the new configuration at Heggernes with five hydrophones, one mounted in keel aspect. The hydrophone in keel aspect was expected to receive no reflections from the surface as these are generally blocked by the vessel.

In the low frequencies interference is found of up to -5 dB for the configuration without the keel hydrophone and in the high frequencies amplification is found up to 2.5 dB. With a keel hydrophone without reflections this steadies to 1 dB for the high frequencies.

It is difficult to make an give a generic indication of the difference between the affected level and the source level. The differences depend on the location of the acoustic center and the measurement configuration under consideration. Therefore it is more useful to determine the difference for each situation individually.

PART II - METHOD

Approach

The debate about the 'source level' and the 'affected level' was already introduced. This is an important debate in light of the current method as this is exactly the main distinction between the initial result of a model and the measured levels it is compared with. In principle the model delivers a source level: no environmental factors are taken into account. It is not possible to account for environmental factors theoretically, because these are dependent on the measurement configuration.

However, this is not final as the goal of the model is to be able to compare to the levels given by measurements, these namely form the basis for the requirements and are the only possibility to validate the result.

The requirements for the model were defined based on the information available during development and the difference between the 'affected level' and the 'source level'. In short the requirements are:

- The model should present the 'source level'.
- The model should provide a quick indication based on limited information.
- The output should be comparable to requirements for underwater acoustic signatures.
- The output should be verifiable with the available measurement data.

The importance of different parameters has been investigated and the thickness and the perimeter of the hull plates have been established as important parameters for the radiation into the water, based on the formulation of the radiation efficiency by Rumerman. Furthermore, the velocity level on the hull is an important result of the SEA model.

Design

The method consists of the components shown in figure 1. The method is split in three parts: the input, the method itself and the output. The components that make up these parts are found in the boxes and are discussed in the following paragraphs.

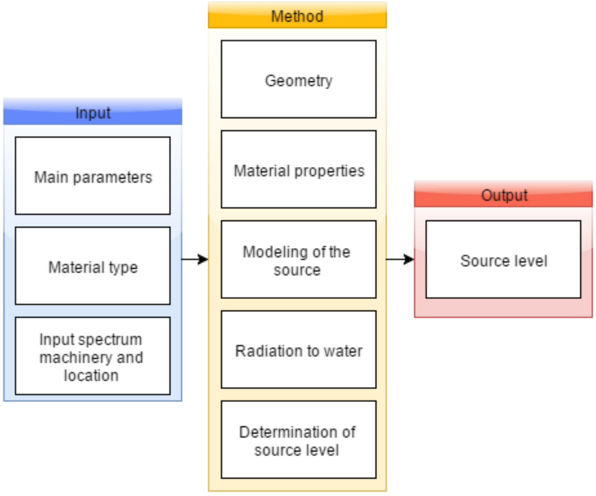

Figure 1: Structure of the model

In order to make the model in SEA, the geometry is scripted using MATLAB. Based on the input mentioned in figure 1, a MATLAB code was developed to generate a script that can be imported in SEA. The model is then created in SEA and can be solved to find the resulting levels in the far field. These results can be used to calculate the sound pressure level at the acoustic center, again in MATLAB. Any radiation function can be incorporated.

Input

he philosophy behind the method was to deliver a simple model and limit the input parameters that are necessary.

The input consists of main parameters, material type, source level and source location. For the validation cases detailed drawings are available, but normally these should be based on a small amount of information. The input for the model is limited mainly to the engine room. The information that should be supplied is discussed simultaneously with the different components of the method.

Components

The different model components were visualized in figure 1 and are discussed in this paragraph.

Geometry

Only the engine room was modeled, since this was the location of the sources, and it was found that the contribution of other spaces was small. The geometry of the engine room was scripted and was based on the main variations found in vessels. The cross-section does not change along the length of the vessel. In the end, the other spaces in the vessels were modeled by adding an aft, top and front space to account for the energy losses that are normally found to these spaces.

The importance of different parameters was determined by a sensitivity analysis and using the formulation of the radiation efficiency by Rumerman. Two parameters that were identified to have a large influence were the edge length of the hull plating and the hull thickness.

Material properties

The material parameters can be based on theoretical representative values. One material parameter showed to have a large influence and was found to pose a modeling challenge: the damping. Damping was generally based on measurement values, but it appeared that these measurement values were not suitable for SEA. The damping was too large if the response on a particular subsystem in the model was compared to measurements of the response on the similar subsystem in the true structure. It is hypothesized that the damping measurements include all losses found in the system and SEA accounts for these losses separately in three factors: the coupling loss factor, the radiation loss factor and the damping loss factor. Therefore, for further modeling theoretical damping values of 1% were used for the damping loss factor. [10]

Source modeling

For the source modeling, the preferred option would be to use power input. A fixed amount of energy is introduced into the system and the properties of the input plate do not influence the amount of energy that propagates through the structure. However, the first model showed that the power input did not result in a representative response. Therefore, a velocity constraint was used. A velocity constraint defines the velocity of the entire subsystem and should be modeled by the average velocity on that subsystem. The amount of energy inserted into the system is dependent on the dimensions of the subsystem, because the energy is proportional to mv^2. The velocity constraint should be modeled carefully, taking into account the characteristics of the plate in SEA and the true structure.

In the future it would be preferable to use the power input. To be able to do so, the relation between power and velocity in SEA should be studied.

In principle multiple sources can be included if the velocity constraint is used. A possible effect is that power is dissipated in one of the subsystems to which a constraint is applied. This takes place if it is necessary to dissipate power to satisfy the constraint for that particular subsystem. The consequences of this for the total result have not been investigated, but is thought to have limited influence. In principle the velocity constraint represents the situation in the true structure and cannot deviate too much from the situation in the model. Therefore, it should be possible to also use multiple velocity constraints to model different sources. This has been applied for different plates that are excited by the same source and did not show any peculiarities. The application should be done with some caution and whether dissipation occurs can be checked by looking at the power losses in the source plate.

Because the model is a linear model for the different source inputs, sources that are completely independent from each other can be included together without any hesitation. It is more difficult when sources are interdependent or are found in each others direct field. For this prediction model this case is not very relevant as only the main sources will be included and the sources are based on empirical data.

It is important to also consider airborne sources. In an earlier publication, it was concluded that vessels built for a low underwater acoustic signature can experience a significant contribution of the airborne flanking sound. [4] During the validation for this model it was also found that the airborne sound was dominant in some cases.

Radiation to water

For now the theory by Rumerman is chosen as a starting point for this model. This is the only theory for underwater radiation that has been validated. This validation was done by an independent party and showed good agreement. [21]

Furthermore, VA One includes radiation theory for radiation into water, but the background of this theory is unknown.

Determination of the source level

The final goal is to express the underwater acoustic signature of the vessel as a source level. In essence it boils down to the fact that VA One provides the velocity levels, dimensions and the radii towards a point in the far field from each plate. This point in the far field is modeled in VA One using a Semi Infinite Fluid (SIF). The SIF is located directly beneath the acoustic center and the z-position of the SIF is established looking at convergence of the difference between two models.

The velocity levels and dimensions are used to determine the power inputs into the fluid and using the radii towards the SIF these are added in the far field as sound pressure levels. The sound pressure levels are determined from the power inputs assuming hemi-spherical spreading. The total level in the far field can be corrected to 1 meter from the acoustic center, this gives the final source level.

PART III - VALIDATION

Data

The measurement data of two different vessels was used for the validation. These will be further referred to as vessel A and vessel B. One is a commercial vessel used for cargo transport and the other is a research vessel. First the simplified modeling method is validated with this data and then the structural model and the underwater levels are validated.

Simplified model

A complete model was available of the engine room of vessel A, including all details of the construction. This allowed for the comparison of a simple and a complete, detailed model and thereby offered the opportunity to validate the simplified modeling approach. A picture of the simple model is shown in figure 2.

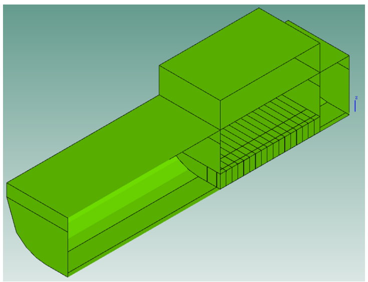

Figure 2: Simple model

For the comparison power input was used to model the excitation, to eliminate the effect of different input plates. The level in the SIF was evaluated, since this is representative for the final output of the method. The difference between the global results of the two models was found to be small. The situation for a generator with and without airborne sound and a shaker was investigated. Depending on the source used on average a difference of 0.7 dB was found over the entire frequency range with a maximum difference of 2.8 dB.

The results are given in figure 3, where the difference between the simple and complete model (simple-complete) is plotted as a function of frequency.

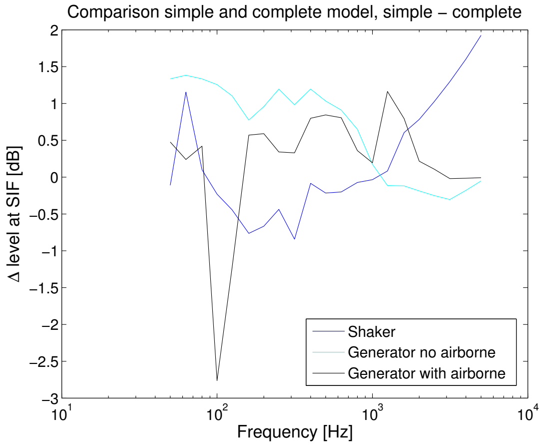

Figure 3: Comparison simple and complete model

The results indicate that it is a just assumption that a simple model can represent the vessel for the determination of the acoustic signature in the design stage just as well as a complete model.

Structural model

It was desirable to get an idea of the performance of the structural model before the underwater levels were evaluated. It is hard to make a good comparison, since the representation of the structure is simplified and therefore it is difficult to find the same location in both structures. The best option was to look at the levels on the hull, which were available for vessel A. This location is most relevant for the underwater acoustic signature and is therefore represented in the model. The validation was done for a shaker and a generator excitation, for the latter the airborne contribution was found to be dominant.

The deviations between the model and measurement levels on the hull were quite large for both the simple and the complete model. For the shaker excitation the deviation was about 6 dB on average and for the generator about 14 dB on average. This was only an investigation of one location on the hull and it is not sure how representative this is. The modeling of the machinery is expected to be at least partially responsible for the deviation and should be investigated further. It should be noted that SEA yields average velocities on an entire subsystem, while the measurements give a representation of the response at a particular location. What the exact effect on the modeling of the machinery and for this comparison is, should be looked into.

Underwater levels

The static measurements of vessel A and B were used for the validation of the underwater levels. These were preferred over dynamic measurements, since no contamination of propeller and flow sound is present.

Before the model could be validated a theoretical approximation of the contribution of reflections to the final level was made. For vessel A these were hypothesized to be negligible as the hydrophone was mounted on the side of the vessel at a large distance from the bottom. The expectation is that the vessel shields the surface reflections. This assumption could not be confirmed or falsified when different measurements were compared.

For vessel B both bottom reflections and surface reflections are present. The bottom absorption is unknown, this makes it hard to make a good approximation. In general in the low frequencies the bottom reflections amplify the level and the surface reflections cancel the level. Together, depending on the bottom absorption, this adds to several decibel below or above the direct level. In the high frequencies the reflections add in this case to about 3 dB on top of the original level. An important factor in the interference found due to the reflections is the vertical position of the acoustic center.

The next step was comparing the results of the model to the results of the measurement, it was found that the radiation efficiency incorporated in VA One gave a better match than the radiation efficiency by Rumerman. It is interesting to investigate what causes this difference, especially because literature indicates that Rumerman gives a proper representation of the radiation of submerged plates. [21] The background of the VA One radiation efficiency is unknown at this point.

Comparing the measurement levels for both vessels for different the runs gives the differences shown in figure 4.

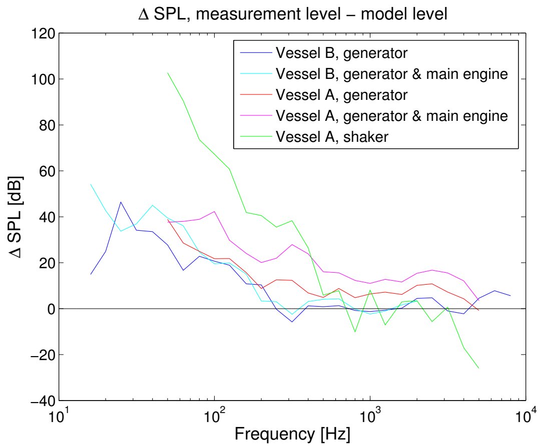

Figure 4: Comparison measurement and model

The measurement results are much higher than the model results in the low frequencies. From 200 Hz on the model of the vessel B gives a much better agreement with the measurements and from 500 Hz also the shaker on vessel A is rather similar. Both the run with the generator and the run with the main engine for vessel A deviate more, this might be caused by the modeling of the sources.

The average deviation for different frequency ranges is given in table 1 for the different cases that were looked at.

Table 1: Average deviation measurement and model [dB]

	f>50 Hz	f>200 Hz	f>500 Hz
Vessel A			
Shaker	32	16	9
Generator	13	8	7
Generator & main engine	21	16	13
Vessel B			
Generator	12	3	3
Generator & main engine	18	3	2

These values were determined not taking into account the reflections, this would change the deviations, but it is not possible to give the exact magnitude of the contribution of the reflections.

PART IV EVALUATION

Conclusions and recommendations

Several different conclusions can be drawn about the components of the method and finally about the results and the performance of the method.

SEA is a suitable method for a prediction like this. A simplified SEA model is as useful as a complete model for the underwater acoustic signature, a global parameter. Scripting allows for the fast and simple generation of several models, making it easy to compare between different options.

The geometry of the model can be established based on global information, but the hull thickness and the size of the hull plates are important for the radiation into the water. The radiation was expected to be best described by the radiation efficiency given by Rumerman, since this function was validated for underwater radiation. Although during the validation it did not perform well. There it was found that the radiation efficiency included in VA One gives the best approximation.

Damping is an important parameter that is currently based on theoretical values. Source modeling is very influential. For this power input would be the preferred approach, but the results found with power input show that it does not give a good representation. Therefore currently velocity constraints are used, but this asks for careful modeling of the source and source location.

The model results show that both for the structural model and the underwater model more research is necessary to use the values for a proper prediction of the underwater acoustic signature. For the onboard levels the source modeling is important to look at and more elaborate measurement data is necessary for further validation.

The choices made for the modeling parameters were based for a large part on the sensitivity analysis that was conducted. This sensitivity analysis included several variations of parameters and provided a first insight into the effect of several parameters. It was useful to evaluate the results at the SIF, because this gives the best comparison with the final result that is looked at and which should correspond as good as possible to the true level. The variations that were done were useful as well, but do not provide enough basis to draw generic conclusions from. The results found between the simple and complete model for vessel A did show that the basis of the model was sufficient for the establishment of a simple model that is comparable to a complete model. It also showed that large differences in geometry and even in hull parameters can be acceptable. Combining these results it can be said that the simplification applied here is good enough, since both are based on different vessels. However, a more elaborate analysis of these results and of more vessels is useful to discover the true nature of several effects. In this case it was chosen to do the parameter analysis with a cross section of a vessel, but a more basic approach is useful as well, looking at very simple items in VA One. It is advisable if a sensitivity analysis is conducted, to use scripting if the geometry includes many subsystems.

The model can be easily applied in the design stage and can evolve throughout the design. The method in its current status cannot be used for exact predictions but offers opportunities for comparison between different configurations.

In the end, it is not possible to conclude whether this method can be applied for the prediction of the underwater acoustic signature. The validation of the underwater levels shows promise in several cases, but others deviate too much. The method gives better results for the high frequencies, which might be caused by the fact that SEA is not applicable for low frequencies. More validation is necessary, especially looking at the source modeling, which probably accounts for a large part of the deviation. Furthermore, it is important to be able to say something about the reflections for the final comparison. It should be noted that the current results yielded by the method are not conservative.

Many subjects have been identified for further research, for example: low frequencies in SEA, modeling of damping and absorption, the modeling of the machinery and radiation. The most important aspect to look into at this point is the radiation efficiency. It was found that the level in the SIF is most useful for comparison between models and to look at the effect of several variations. The radiation efficiency is a parameter that influences this significantly and at this point it is not sure how this is represented best. Therefore, the first step would be to determine the radiation efficiency. Another important aspect is the modeling of the machinery, for this an approach should be defined to be able to easily model with velocity constraints, based on average velocity levels. It is also possible to focus on enabling the use of the power input, by looking further into the working principles of this option in SEA.

At the moment the method can be used for the visualization of the response of the hull and for the determination of the relative importance of design choices. For these analyses it should be kept in mind that the radiation efficiency is influential and is not validated yet. If the method is validated further and found successful then aspects that can be looked into are: further simplification, automation of the method and application for other materials.

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