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PUB – Methods to predict radiated ship noise

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Prediktionsmetoder för utstrålat fartygsbuller - PUB

Methods to predict radiated ship noise

Development and comparison of methods to assess and predict the underwater radiated noise from ships through sea trials, model scale experiments, and computational fluid dynamics simulations.

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Summary

Continuous underwater noise from shipping has received increased attention recently. The work presented in this report, focuses on the issues and our ability to predict the underwater radiated noise (URN) from a ship, during the design phase as well as assessing the performance of an existing vessel. Although standards and procedures are improving, it is not straight-forward to provide a fair assessment across different techniques and locations.

In PUB, we performed measurements of URN for a coastal tanker in (1) a controlled sea trial, (2) cavitation tunnel model scale experiments, and (3) CFD simulations in both model and full-scale. The results were compiled and jointly analyzed to identify, describe, and understand discrepancies between the various techniques. Using CFD, we also analyzed effects of scale and confinement (blockage) in the cavitation tunnel experiments in relation to full-scale conditions. Further, a technique to compute URN in CFD were developed with the ambition to find a reliable and relatively cost-efficient method compared to what is often used in literature today.

We can see large discrepancies in the outcome from the different methods and in the two scales. A main uncertainty in the comparison is the contribution of URN from the machinery system on the vessel, captured in the sea trial measurements but not considered in the cavitation tunnel experiments or the CFD. It is anticipated that machinery-generated URN is large in relation to propeller induced URN in this case as the cavitation extent is rather limited in the experiments and CFD. In the model tests, part of the discrepancies is related to intermittency in the cavitation dynamics. For the CFD, we are not resolving the flow dynamics in the ship wake and tip vortex cavitation is only captured to a limited extent, leading to under-predicted URN. The scale and blockage effects are noted to be significant, and they cannot be accurately represented by recommended scaling procedures. The new procedure to compute URN from CFD appears to perform well and give similar level of accuracy with a higher robustness than previous method.

A final useful outcome of the project worth highlighting is the network developed between participating partners. We have through PUB developed a small but active community working with URN from shipping in Sweden with a high international recognition.

Sammanfattning

Kontinuerligt undervattensbuller från sjöfarten har fått ökad uppmärksamhet på senare tid. Arbetet som presenteras i denna rapport fokuserar på detta problem med fokus på vår förmåga att förutsäga det undervattensutstrålade ljudet (URN) från ett fartyg under designfasen samt att bedöma URN emissionen hos ett befintligt fartyg. Även om standarder och rutiner förbättras är det inte fullt klarlagt hur man ska ge en rättvis bedömning av ett fartyg som URN-källa genom olika analystekniker.

I PUB utförde vi analys av URN för en kusttanker i (1) under en kontrollerad provtur, (2) experiment i modellskala i kavitationstunnel och (3) CFD-simuleringar i både modell- och fullskala. Resultaten sammanställdes och analyserades gemensamt för att identifiera, beskriva och förstå skillnader mellan de olika teknikerna. Med hjälp av CFD analyserade vi också effekter av skalskillnader (modell- till fullskala) och den begränsade domänen i kavitationstunnelexperimenten (blockering) i relation till fullskaliga förhållanden. Dessutom utvecklades en teknik för att beräkna URN i CFD med ambitionen att hitta en pålitlig och relativt kostnadseffektiv metod jämfört med vad som ofta används i dagens litteratur.

Vi kan se stora skillnader i utfallet från de olika metoderna och i de två skalorna. En viktig osäkerhet i jämförelsen är hur stort bidrag till URN från maskinsystemet på fartyget. Detta bidrag är inkluderat i provtursmätningarna men beaktades inte i experimenten eller i CFD:n. Det förväntas att maskingenererad URN är relativt stor i förhållande till propellerinducerad URN i detta fall eftersom mängden propellerkavitation är ganska begränsad i experimenten och CFD. För modellförsöken är en del av avvikelserna relaterade till intermittens i kavitationsdynamiken, d.v.s. kavitation uppstår inte på varje propellerblad. I CFD:n löser vi inte strömningsdynamiken i skeppets kölvatten och spetsvirvelkavitation fångas bara upp i begränsad utsträckning, vilket leder till underpredikterad URN. Skal- och blockeringseffekterna noteras vara betydande, och de kan inte korrekt representeras med rekommenderade skalningsprocedurer. Den nya metoden för att beräkna URN från CFD verkar prestera väl och ge liknande noggrannhet med högre robusthet som tidigare metod.

Slutligen har projektet medfört att medverkande parter har utvecklat ett starkt nätverk, med gott internationellt anseende, inom området kring undervattensbuller från fartyg.

Contents

1 Introduction

The awareness about the increasing environmental pressure from underwater radiated noise (URN) caused by shipping is increasing (Duarte *et al.,* 2021; de Jong *et al.,* 2025). The main scientific challenge is to clarify the chain of ecosystem impact – environmental pressure – in situ monitoring – ship operation and design. Several efforts are ongoing but there are still knowledge gaps to fill. There is a need to understand at which sound levels and in which frequency ranges ships emit noise and how this leads to an environmental pressure; what this pressure constitutes for the marine wildlife and the ecosystem; how this pressure is affected by the marine environment in different locations and under various conditions due to variations in bathymetry, sediment and water properties; how to measure and interpret noise emissions and what regulations and policies should be implemented to mitigate the effects on the environment; and how a ship should be designed and operated to comply with regulations and be considered to have a low environmental impact. The PUB project has mainly aimed at the last links in the chain, primarily in how to assess the underwater radiated noise (URN) emissions from a ship, during the design phase and when built.

It is generally recognised that propeller cavitation is the main source of noise for most ships at normal speed. An example is shown in Figure 1, where the difference between non-cavitating and cavitating operating conditions is approximately 20 dB in one of the frequency ranges that affect marine wildlife (63-125 Hz, the blue band in the figure); for a more detailed description of how noise is considered to affect wildlife, please refer to the review by Duarte *et al.* (2021). Of course, there are large variations between different ships, but the example can be considered typical. At lower speeds and at lower frequencies, however, cavitation may be expected to be lower or absent, implying that noise from the machinery system may also be substantial and potentially dominating. Since machinery-generated noise is transmitted to the water via the hull, measures to reduce this contribution involve how the structural characteristics of the hull are designed and how the engine is assembled, which are relatively well-known design choices. Further, we note that this contribution should be expected to be fairly independent of ship speed and operation.

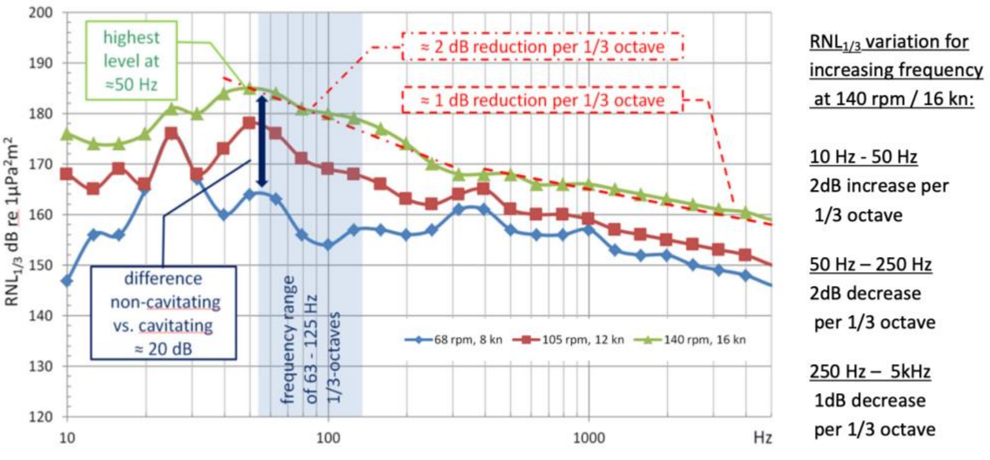


Figure 1 Example on underwater radiated noise level from a bulk carrier vessel at different speeds, from Baudin and Mumm (2013)

The main measure proposed today to reduce noise is to reduce the speed so that cavitation does not occur. This may be conceivable during short passages but during transit, this is not an acceptable solution. It leads to longer transport times, increased costs, and not the least, potentially increased climate impact due to increased emissions as the ships go outside their operational profile for which the ship is designed for a longer period of time. For certain types of vessels, such as research vessels and cruise ships, and increasingly for fishing vessels, active design work is underway to delay the start of cavitation, i.e. ships are given the opportunity to steam slightly faster before it starts to cavitate. But this leads to a deterioration in the efficiency of the propeller and thus again increased air emissions. These measures are also not sufficient when it comes to the ships that make the major contributions to underwater noise: container vessels, tankers and bulk carriers – the ships that play a major role in global trade. There is thus a need for tools and knowledge that allow for the design of less noisy vessels, and to be able to make informed choices in investment of technologies or operation to be able to minimise and balance energy efficiency and underwater radiated noise.

1.1 Presentation of noise emissions from ships

In this report, we will primarily use the Source Level (SL) in the discussions on the results. This is a measure commonly used to describe the ship as a source of URN. When measuring the sound at the hydrophone, the received signal of acoustic pressure fluctuations is represented as Sound Pressure Level (SPL) expressed in the logarithmic unit decibels relative to a reference pressure of 1 μPa, dB re 1 μPa or dB re 1 μPa / Hz as a function of frequency, cumulated in frequency bands of different bandwidth as indicated in each case. To represent the source, the SL, the measured SPL needs to be back-propagated to the ship, to a normalised distance of 1 m, by deducting a transfer function, derived from measurements or modelling as outlined below in Section 1.2.2. In a simplified process, one can use only a distance compensation instead of more detailed transfer function; then the result is called Radiated Noise Level (RNL).

1.2 Knowledge gaps relevant for PUB

The available knowledge and tools for measuring and predicting cavitation and the associated underwater noise generation are still insufficient to design and reliably measure differences in noise between ships with different propulsion systems. The focus of this project has been to enhance our tools for assessing the URN emissions from a ship, both during design and for final evaluation during sea trials, as well as to improve the interpretation of results from each tool. This has involved numerical tools based on Computational Fluid Dynamics (CFD), model-scale experiments, and full-scale sea trials. Each approach presents its own challenges, summarised here.

1.2.1 Numerical and experimental prediction of URN

The traditional method to assess URN before the ship is built is through model tests in a cavitation tunnel or a depressurised basin. A number of studies (Hallander, 2020; Tani *et al.*, 2020) have shown that if you compare measurements of the noise level of one and the same propeller but in different test facilities, you can get differences of 10-20 dB in reported SL in certain frequency bands, and in some cases even more. Using a logarithmic dB measure means that the reported differences of 10-20 dB indicate a power difference of 10-100 times depending on the facility in which the measurement has taken place. This large difference manifests itself despite that existing recommendations for how the test should be carried out are followed (ITTC, 2017). However, although scale model experiments and scaling laws are a mature field, there are several physical differences between the real full-scale environment and a cavitation tunnel that are difficult to compensate for, e.g. the limited acoustic environment in a cavitation tunnel and the water quality (Tani *et al.*, 2020); this will then also vary between facilities.

There is about the same magnitude of difference if you compare experiments with calculations (Bensow *et al.*, 2016; Li *et al.* 2018). The challenge lies in both predicting propeller cavitation correctly and calculating the radiated noise it will generate. Sheet cavitation and its interaction with incipient tip vortex cavitation is driven by the passage of the propeller through the ship wake and is only possible to predict in some cases (e.g. Ge *at al.*, 2020) in model scale; for full scale conditions there are still only a few studies related to the prediction of propeller cavitation, especially in the case of a ship configuration.

Furthermore, significant uncertainties exist regarding how to calculate the URN caused by cavitation. In aeroacoustics, far-field noise is typically calculated using acoustic analogies, mainly the Ffowcs Williams–Hawkings (FW-H) method. This method was developed to avoid costly direct computations of sound propagation, relying instead on an integration of sound sources and an integral equation for propagation. Its fundamental assumption is that sources are computed with a compressible simulation model, the flow is single-phase, and the sources are located in free space; all of which are formally violated when calculating ship cavitation noise. Despite this, it has been frequently used in literature for cavitation noise by sampling pressure variations on a virtual permeable surface that encloses all sound sources, without regard to these limitations. However, there are indications that this could lead to inaccurate predictions (Ahmed, 2020; Ge *et al.* 2022; Vikström *et al.* 2022).

1.2.2 Sea trial measurements of URN

Standardization of underwater noise measurements is evolving. At the project start, an ISO standard existed only for measurements for deep water (more than 150 meters) (ISO, 2019), and just recently, after the project end, a standard for shallow water has been released (ISO, 2025). Further, several classification societies have developed their own standardized measurement and analysis procedures, e.g. DNV (DNV, 2021); Lloyd's Register (LR, 2018); and Bureau Veritas (BVC, 2018).

The greatest uncertainty when measuring radiated noise is often the sound propagation between the vessel and the measurement hydrophone. For best accuracy at long ranges, it is required that careful investigations are made of the acoustic environment in the sea where measurements are performed, since measured data are affected by the topology and properties of the seabed, sea temperature and salinity; the latter can vary from one measurement time to another. This information is typically not completely accessible which limits the possibility to model the propagation. Even when trying to measure the sound propagation, e.g. by using a loudspeaker as a known source, challenges remain in taking full consideration of the environmental conditions in the full frequency range, due to e.g. speaker limitations. Further, the angle between the sound source and the surface affect propagation behaviour. Some measurement guidelines only use the simplified assumption that propagation can be modelled as $M\log(R)$, where R is distance and M is a constant between 17 and 20. This can lead to large deviations if, for example, the sound-velocity profile in the water differs substantially with depth or the seabed is highly reflective. Thus, converting measured sound levels to representative SL that can be compared with corresponding predictions or regulations pose a challenge. Recently and after the end of the PUB project, ISO published a new standard for measurement of URN at shallow waters, which includes a new analytical method for calculating transmission loss at relatively short ranges (<300 m). This is expected to alleviate the aforementioned difficulties to some extent.

Through series of measurements, several models of a ship URN emission have been developed over the past fifteen years (McKenna *et al.*, 2012; Wittekind, 2014; Jalkanen et al, 2018). However, these measurements may not have been carried out according to sea trial standards, and the models may rely on technical data and empirical relations. Further, e.g. in the ECHO project (MacGillivray *et al.* 2019), statistics of the signature of a large number of deep-sea vessels were collected opportunistically at two speeds, later used to develop a statistical model for ship noise (MacGillivray and de Jong, 2021). It's important to note that these measurements and models are thus not intended to assess a single ship but the cumulative impact and to develop statistics. For these datasets and models, the issues on accuracy of the standard sea trials described in the previous section still holds, and moreover, information regarding ship operating conditions may not be fully known.

1.2.3 Effects of uncertainties on ship design and operation

The differences, as previously discussed, can be up to 20 dB between various predictions and measurements. This makes it impossible to detect differences in design or operational decisions where differences of 3-5 dB are relevant and realistic, ultimately exerting a decisive influence on environmental pressure.

As a result of this situation, there is currently not enough knowledge or tools to confidently distinguish one quiet propeller design from another. There is a basic understanding of how cavitation dynamics affect noise, but since the analysis methods are too blunt, several issues may prevent a progression towards quieter ships. One aspect is that the development of URN mitigation may lead to lower propulsive efficiency with higher emissions to air as a result, if design margins need to be too high. Preliminary results presented at the IMO (IMO, 2025) indicate that by redesigning the propeller, without any other energy efficiency or operational changes, one can expect about 1% reduction in propulsive efficiency for a URN reduction of 3 dB. This result then relies on a precision in the URN prediction that is better than 3 dB, which is questionable. Further if, the predictions can't correctly represent the effect of a mitigation measure, wrong design or operational decision might be taken, missing an opportunity to reduce ship URN. It should be stressed that if actions are taken to improve the energy efficiency of the ship or its operation, significant reductions can be expected also for URN emissions.

1.3 Project objectives

The goal of PUB was to reduce the knowledge gap about the direct link between propeller design and the noise emissions of a ship to the sea, and thus the possibility of designing a ship that is both quieter and has high propulsive efficiency. To achieve this goal, PUB was composed of three dedicated studies for one ship, a Terntank vessel (Figure 2): a dedicated sea trial measurement of URN; an experimental campaign in the RISE cavitation tunnel; and assessment and development of methods for computational predictions of URN. The latter also included studies on how scale effects and cavitation tunnel blockage, affect the ship URN.

Thus, one part of the objectives was to develop and evaluate prediction methods for ship-generated noise to improve their accuracy and reliability. This includes improved and more efficient computational tools that can be used in a design phase, improved understanding of measurement routines and their impact on the results, and an analysis of the discrepancies between different prediction methods.

An important interim objective was to carry out the detailed full-scale measurements, including sound propagation measurement, in order to provide better knowledge of how our prediction methods work in reality and an expanded ability to interpret future continuous measurements in our waters.

Finally, the project should bring together different Swedish cutting-edge competencies on ship-generated underwater noise and thus offer opportunities to expand knowledge and collaboration between industry, institutes, and academia on these issues.

Figure 2. The investigated ship Tern Island, photographed during the full-scale URN *measurement outside Vinga in the Gothenburg archipelago, September 2023.*

2 Sea Trial measurement campaign

The planned measurements on the ship included both analysis of data from the fixed hydrophone that FOI had mounted outside Vinga in connection with the JOMOPANS project, and dedicated sea trial measurements within PUB. Unfortunately, the fixed hydrophone had to be dismantled due to lack of continued funding and that data was only used for planning the sea trial measurements. The sea trial measurements are separately reported in Andersson *et al.* (2024).

The measurement trials were performed approximately 1.7 km south-west of the islet of Vinga in the Gothenburg archipelago. The area has a flat bottom with a water depth of around 45 m, known to consist of mostly clay and mud. The ship source level measurements and propagation loss measurements took place one week apart in 2023. Both days were very calm with low wind speeds and wave heights below 0.5 m. However, turbidity was high due to windy conditions the week before that prevented planned visual assessment of cavitation extent during the tests.

A total of eight hydrophones were used during the measurements, see Table 1 and Figure 3. The placement of these hydrophones was chosen to evaluate effects of different placements in relation to what is typically used in deep water measurements and in other studies involving shallow water conditions; note that at the time there was no standard issued for URN measurements in shallow waters. Thus, a combination of vertical arrays at distances longer than one ship length, as typically required by many deep-water measurement methods, and closer hydrophones to achieve the also required higher grazing angles, i.e. between the water surface and the line from the ship to the hydrophone, was used. In addition, a hydrophone was placed directly under the keel of the ship. The purpose of this was to determine if such a measurement position provided results comparable to the other positions. Further, two pressure transducers were mounted in the hull above the propeller to measure the pressure pulse levels. An accelerometer was also installed to measure hull plate vibrations. Ship operation was monitored through communication with the crew during the trials and later analysed through the Kongsberg Vessel Insight ship monitoring system installed on the vessel. The system was also complemented by a GPS receiver measuring speed over ground (as the monitoring provides speed through water).

Table 1 Placement of hydrophones relative to measurement track, and their deployment heights above the bottom.

Hydrophone	**Distance from track** [m]	**Height above bottom** [m]	**Grazing angle** [°]
Colmar 1	-165	2	14.6
Colmar 2	-165	12	11.3
Sylence 1	0	2	90.0
Sylence 2	220	2	11.1
SoundTrap 1	35	2	50.9
SoundTrap 2	70	2	31.6
SoundTrap 3	70	20	19.7
SoundTrap 4	220	15	7.8

Figure 3. Hydrophone placement during sea trial. The ship travels inwards/outwards of the figure.

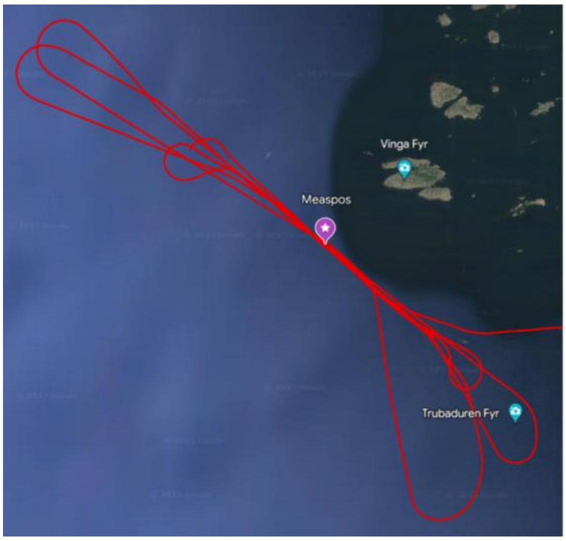


Figure 4. Ship tracks during sea trial. "Measpos" indicates the point where the ship crossed the line of hydrophones.

Propagation loss measurements were performed using a small drifting vessel with a sound source producing a series of chirps in several decidecade bands, repeated through five passages. A reference hydrophone was placed on the vessel and cross-correlation analysis was performed to ensure the quality of the artificial source. The received signals at the other hydrophones were treated with a three-step processing to arrive at the calculated propagation loss for the decidecade band:

1. pulse compression in the frequency domain,
2. selection of a time segment around the compressed pulse in the time domain,
3. frequency averaging of the received level within the decidecade band.

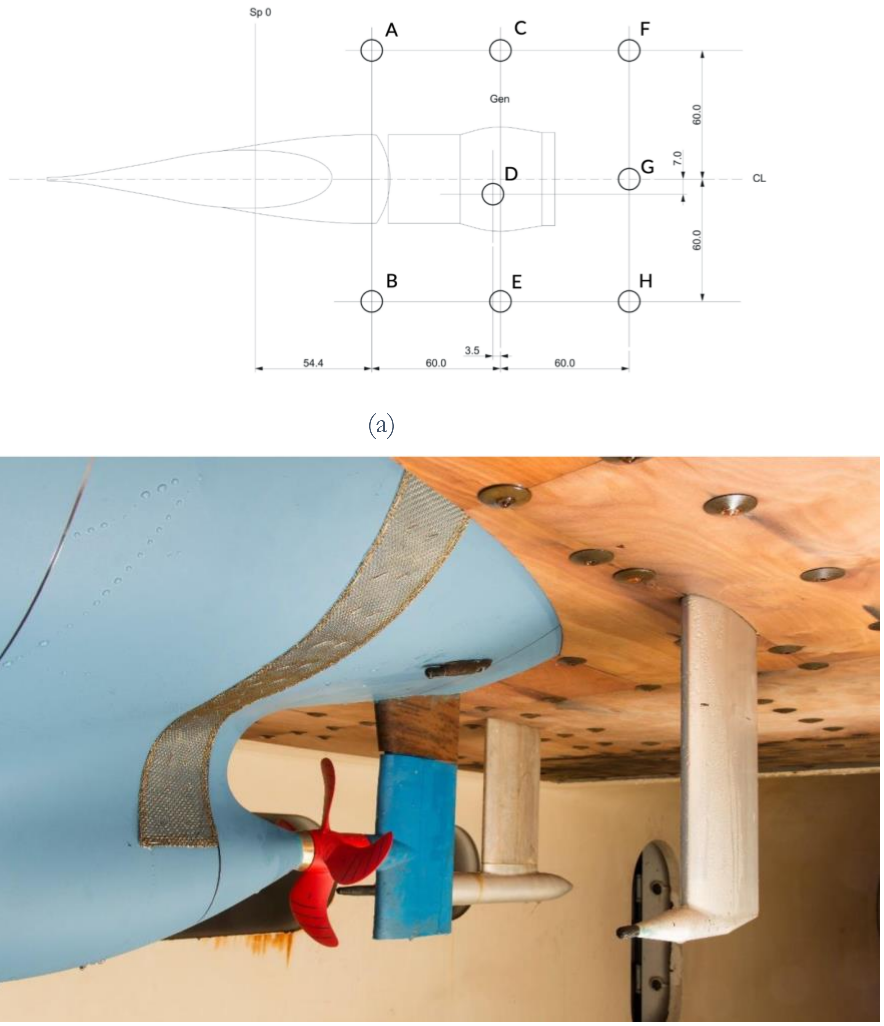
The purpose of these three steps was to increase the apparent signal-to-noise ratio of the measurement, by discarding background noise data known to not be part of the transmitted signal. The measured propagation losses were compared with the simple "seabed critical angle" (SCA) propagation loss model (MacGillivray *et al.*, 2023). The measured propagation loss was found to have a somewhat large spread, with a 3 dB root mean square deviation from the propagation model. Unfortunately, the measurement scheme clustered the high frequency chirps at farther ranges, which limits the insights that can be drawn from this measurement. Further, the measurements indicate that the seabed was very soft with almost fully transmissive properties and the sound propagation can therefore be considered to be closer to a deep water situation than indicated by the water depth alone.

During the trials, the ship made in total seven passages past the hydrophone line. The ambition was to make the runs at the design speed of 14.5 kn. After the first three runs, it was clear that the intended speed was not reached, and it was decided to reduce the speed to 13.5 kn. However, there was a slight acceleration also during the passages at 13.5 kn, but this was considered acceptable. Measured shaft speed and power were kept constant throughout the trials. The rudder angle varied more than expected during the passages, which might have had an effect on the speed.

3 Model scale experiments

Tests were performed in the cavitation tunnel at RISE using a model built at a scale factor of α = 27.143. A new hull model was produced at RISE, and Kongsberg provided the propeller and rudder models. The model was mounted in the cavitation tunnel at even keel conditions. Eight pressure sensors were mounted in the hull above the propeller according to Figure 5. Here, one sensor was in the same position as one of the pressure transducers at the full-scale trials. Three hydrophones were used with two mounted on starboard and port side of the model on struts and one on the hull upstream of the propeller.

Six conditions were tested, two matching previous tests that had been performed at Kongsberg with a dummy hull model during the design of the vessel, and four variations corresponding to the sea trials in PUB. Among these four, one corresponds to the speed and power during the sea trials and one where shaft speed matched the trials but leading to a somewhat higher power. The third variant corresponds to the wanted sea trial conditions at CSR power. Lastly, a lower power was tested to complement the test matrix.



(a)

(b)

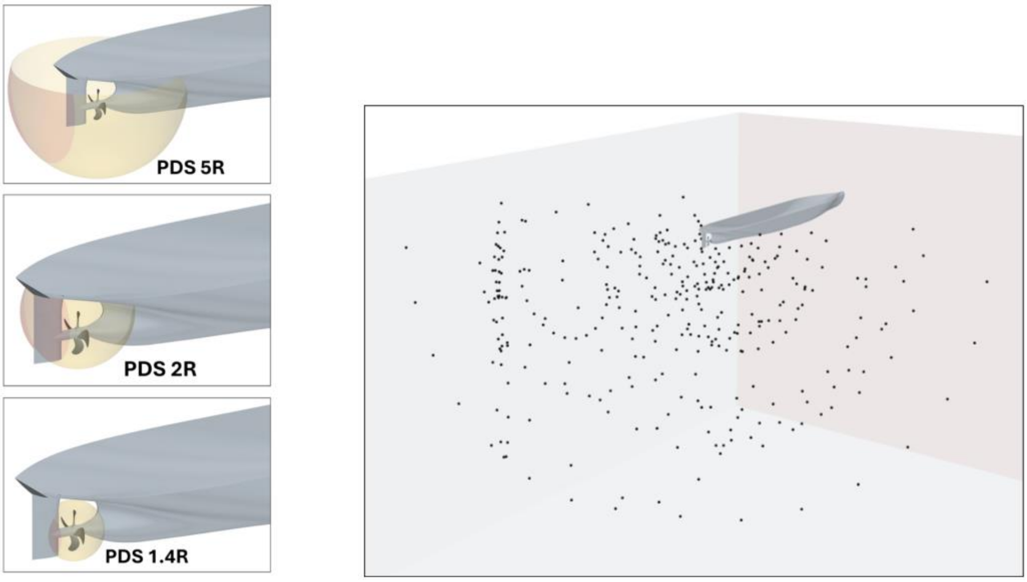
Figure 5. Pressure transducer placement (a) and hydrophone placement (b) during the model tests.

4 Development of CFD assessment methods and studies on scale effects

To advance on the topic of numerical predictions of URN emissions, we followed two paths in PUB. One was to study further the potential reliability risks in using the so called Ffowcs Williams - Hawkings (FW-H) method and develop computational procedures to limit the issues, and the second was to investigate and further develop a simpler approach based on approximations and analytical relations. The intended benefit of the second approach was both to provide more reliable predictions but also do this at a lower computational cost. A complete description of the methods, the rationale, and detailed results are available in the licentiate thesis of Khraisat (2025).

All simulations in PUB were done with state-of-the-art industrial limitations in mind and were thus performed using a RANS (Reynolds-Averaged Navier-Stokes) approach with a transport equation model with mass transfer to account for cavitation, with a rotating propeller. This means that the simulations represent the unsteady average flow around the ship but not considering small scale turbulent flow fluctuations that occur in this kind of flow. The approach has been shown to give reasonably reliable results for hull pressure pulses and cavitation extent in model scale (e.g. Ge *et al.* 2020).

Based on previous studies (Ge *at al.*, 2022; Vikström *et al.*, 2022), simulations were set-up with a series of spherical permeable FW-H surfaces of varying sizes, 1.4R, 2R, and 5R where R is the propeller radius, centered around the expected main acoustic center. Further the effect of mesh resolution was studied, both with respect to cavitation prediction and for FW-H noise predictions.

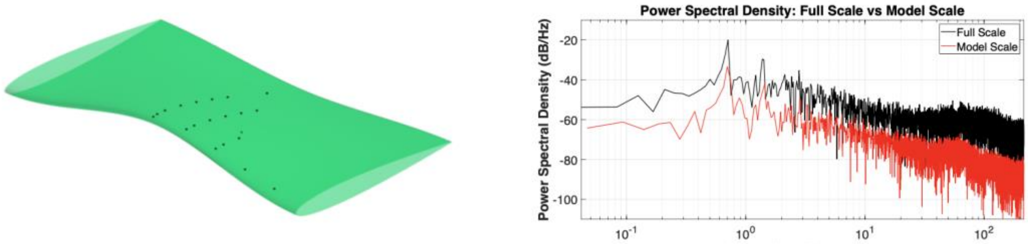


(a) (b)

Figure 6. The three virtual permeable surfaces for the FW-H method tested (a) and hydrophone placement in the CFD (b).

The new hybrid analytical numerical approach investigated consists of considering the propeller cavitation noise as spherical bubble, for which there is an analytical expression for radiated sound as a function of the acceleration of the vapor volume of the bubble. Vapor volume is then sampled during the simulations, differentiated twice, and the radiated sound computed. One difficulty with this approach is that the sampled volume is a discrete signal that is not directly differentiable; here a LOWESS (locally weighted scatterplot smoothing) regression was performed to limit the introduction of spurious transients in the signal.

As noted in the introduction, prediction of URN emissions requires both the correct prediction of cavitation dynamics and the prediction of radiated sound. At present, we have good understanding of our capacity to compute the cavitation dynamics in model scale, but studies on how the flow scale affects cavitation are very limited. To gain insight into this matter, a three-dimensional foil was initially studied in model scale (MS), see Figure 7, a standard cavitation test case where there are published experiments and simulations, and in a hypothetical full scale (FS). The purpose was both on studying how cavitation dynamics change per se, but also to develop the computational requirements for full scale cavitation simulations. The outcome of these studies was used in the ship scale simulations for Tern Island but not further discussed here; see Khraisat (2025) for more details.

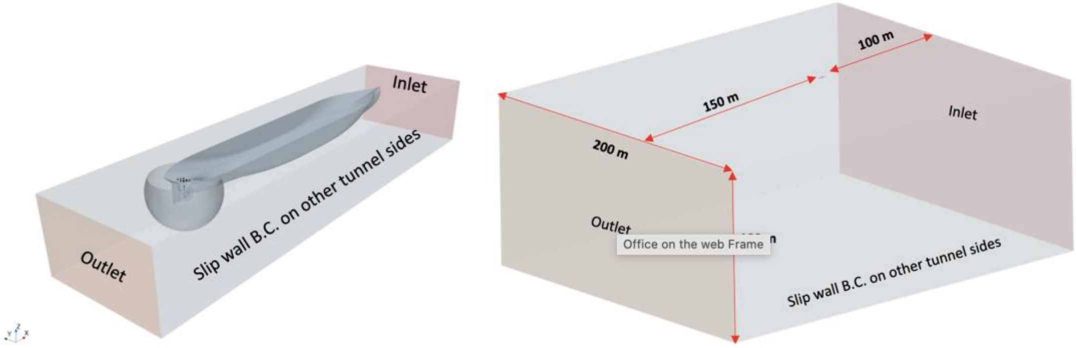


(a)

(b)

Figure 7. The twisted foil (a) used in studies related to prediction of scale effects on cavitation dynamics. In (b), the power spectrum for a recorded pressure signal is compared in model and full scale for the cavitation on the twisted foil.

One further complication in comparing the different URN prediction methods is that the sea trials were performed in a relatively open ocean (the shallow water effects on propulsion are deemed limited in the area, and the bottom sediment was found to be close to transparent for sound) while the model tests were done in a confined space. With CFD, we studied the effect of the model in the confined cavitation tunnel (called TD in the continuation) compared with a large open domain (called LD) with respect to flow dynamics. It was not part of the project to study the direct effect on sound propagation from the cavitation tunnel walls.



(a) (b)

Figure 8 Computational domains for model scale studies on blockage effects (a) cavitation tunnel domain (TD) and (b) the large open domain.

5 Results

The combined distilled results from the work are shown in Figure 9. This plot shows the resulting source noise level in 3rd octave band computed from the sea trials, the cavitation tunnel experiments, and CFD computed for full scale (FS) conditions and model scale (MS) conditions both in the confined tunnel domain (TD) and an open large domain (LD). The legend notations of A-N+S-FWH indicate the new hybrid Analytical-Numerical approach, and the FW-H (PDS 5R) denote the FW-H method with a permeable spherical surface of size 5R. As is apparent, there are large discrepancies between the predictions. Ideally, a precision of around 3 dB would be needed to give confidence in quantifying effects of mitigation measures. It's however important to note that to make that kind of decisions it would suffice to be able to accurately predict noise level changes, something that is not investigated here. Some of the origins of these discrepancies have been identified and are discussed in the following paragraphs, some are still under investigation, while some are unknown and subject for further studies.

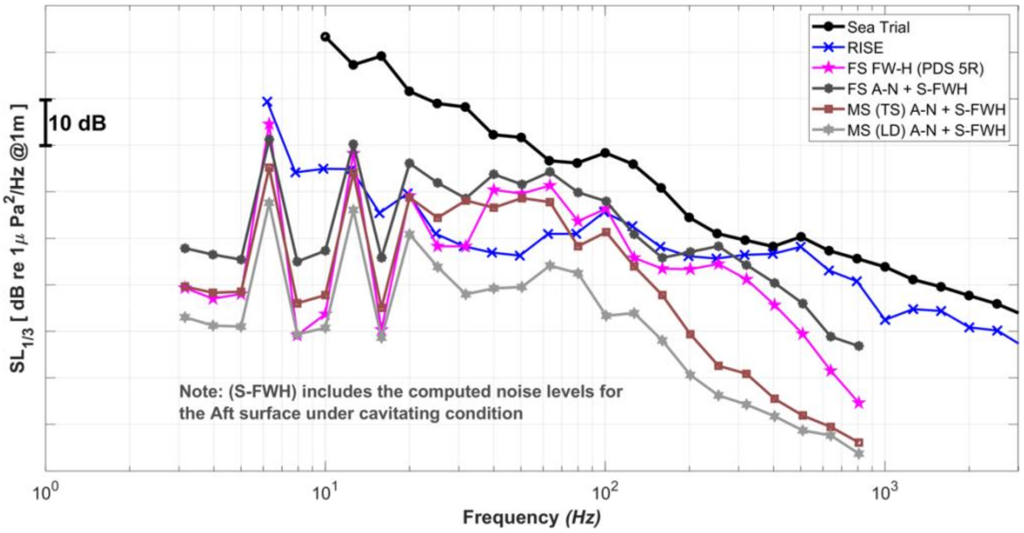


Figure 9. Monopole underwater noise Source Level (SL) from experimental measurement, both sea trials and cavitation tunnel (RISE), and CFD using the developed method for model and full scale conditions; all model scale results are scaled to full scale following ITTC guidelines. See text for further explanation of the legend.

While it may be reasonable to treat the sea-trial results as ground truth, this is not fully justifiable. Naturally, the signal picked up by the hydrophones is the sound that an animal would experience at that position and time, but the source level as presented in Figure 9 is recomputed as a characteristic of the vessel in ideal conditions, and that includes some constraints. As described above, the propagation from the vessel to the hydrophone needs to be inversed. Here, we attempted to measure the propagation loss, and this was deemed rather successful, although with a low frequency limitation. Further, the analysis indicates that effects of the shallow water depth where the tests were performed exist but are limited, at least in the frequency range above around 100 Hz. Also, we are confident that the large gap at frequencies below around 50 Hz are due to noise from the machinery system on the vessel, and these sources are not considered in the cavitation tunnel experiments and in the CFD. This conclusion is based on that the tonals in the low frequency range can be matched with tonals measured for the machinery system; in addition, relatively mild cavitation was detected in the experiments and the CFD.

The exact frequency where propeller noise starts to dominate machinery noise is however not known. It's worthwhile to note that the sea trials were done at two conditions, as the first three passages were attempted at a higher speed, but as that speed was not reached a lower speed was used for the following four passages. For these two sets of conditions, the measurements indicate a difference of 3-5 dB in the broadband range, with lower noise levels for the lower speed. This thus indicates that the sea trial measurements have a precision that can detect these changes in operation. It's also interesting to note that this difference occurred only in the broadband range, while the low frequency tonals were of similar amplitude; perhaps a further indication that low frequency was in this case dominated by machinery noise and thus unaffected by vessel speed.

In an attempt to assess the effect of machinery noise, we used the PIANO model (Lloyd *et al.,* 2024) to estimate the SL for the engine. In Figure 10, we compare the sea trial measurements with the predictions from the full-scale CFD with an engine contribution from the PIANO model. Note that we here only consider the main engine and not auxiliary systems. Further, the full PIANO model includes modules for propeller and cavitation noise as well, but this requires a calibration that is not feasible to do in this study. We note then that the predicted SL is almost completely dominated by the engine contribution up to 200 Hz with good agreement in the range from 40 Hz up to 300 Hz. Below 40 Hz, the sea trial SL is still much higher; this might be due to that the PIANO model does not correctly represent Tern Island for these lowest frequencies, in combination with a larger measurement uncertainty in this range.

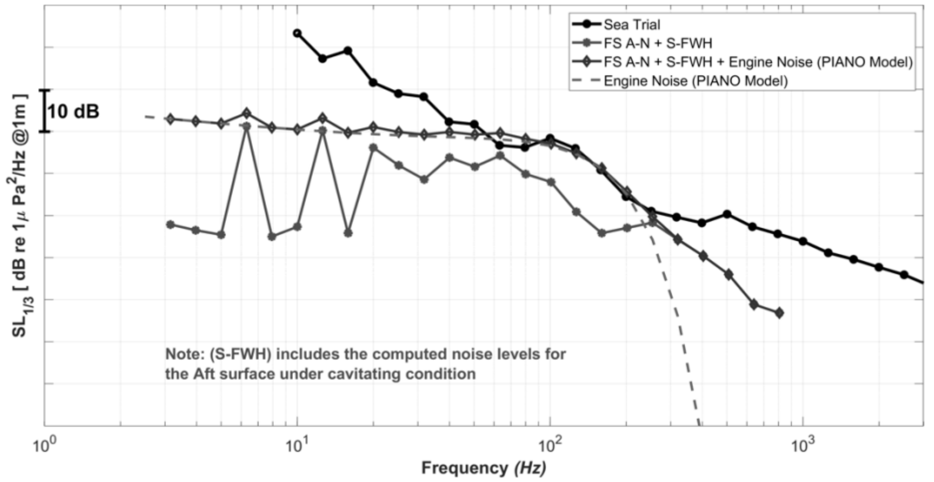


Figure 10 Monopole underwater noise Source Level (SL) from sea trials, CFD predictions of cavitation noise, and main engine noise from the PIANO model.

The cavitation tunnel experimental results overall predict a lower source level compared with the sea trials. Apart from the lower frequency range, the shape of the curve is reasonably well captured. There is an indication of a broadband hump at 100 Hz, then a levelling out of the source level and a rather good match in the decay in the higher frequency range. All experiments suffer from complications with scale effects, a discussion largely postponed to a later paragraph. An issue noted for these experiments was that cavitation was quite intermittent in the condition of the sea trials; by this we mean that cavitation did not occur on every blade passage due to a combination of low content of bubbles in the cavitation tunnel compared with the ocean and laminar flow on the propeller blades (due to the small propeller). This is considered to be the main reason for the underprediction of the hump at 100 Hz. An unknown source of error is that the transmission function of the cavitation tunnel could not be successfully used in these experiments, so the sound propagation could be tainted by reverberation of the tunnel.

When it comes to the CFD results, the ambition was to both develop a more robust prediction method and complement the measurements. The latter was done by performing simulations both for the cavitation tunnel experiment set-up and the sea trial set-up in model and full-scale, analyse the effects of both domain and scale separately, and thereby bridge the analysis between approaches. In general, we note an underprediction in all studies compared with the sea trials. For the full-scale analysis, the curve looks like it's shifted in frequency, but this should not be the case. Instead, we believe the differences are due to an underprediction of dynamics in cavitation due to the use of the RANS modelling approach that models only the average flow; in addition, capturing the tip vortex cavitation is very demanding and not fully successful here. This concerns both the hump at 100 Hz and the decay above around 300 Hz. For lower frequencies, we repeat that the machinery noise is lacking in the CFD analysis.

For the model scale analysis in the tunnel section, the CFD predicts higher levels compared with the experiments in the range 20-80 Hz and then drop off much faster at higher frequencies. Also here, just as described above for the full-scale analysis, the CFD suffers from the modelling approach not properly capturing the tip vortex dynamics causing the fast decay. The difference in the medium-low frequency range may be related to the fact that the CFD does not suffer from the intermittency as the experiments did and may thus constitute a better representation here. Finally, it's interesting to compare the CFD results in model scale when using the large domain and the tunnel section domain. Then the large domain result shows considerably lower source levels, which is due to the change in wake which becomes wider in the large domain and then reduces the cavitation dynamics. This seems to form an unintentionally positive effect from the blockage in the cavitation tunnel, making the predicted SL closer to the full-scale predictions, but this requires further analysis to be conclusive.

In the studies on scale effects, we noted that the cavitation dynamics per se do not seem to be much affected. Some details in the flow changes causing some shifts in natural frequency levels and amplitude of fluctuations. More important are the changes in the propeller inflow going from model to full-scale. As the wake for the real vessels is thinner and has lesser extent from the hull, the load variations for the propeller are also smaller. Thus, the cavity does not develop as early and does not reach the same size, which leads to lower levels of pressure pulses in full-scale compared with model scale. Interestingly, the predicted noise source levels are still higher in full-scale. This might be related, at least in part, to the ITTC procedures to scale the source levels which does not consider any detailed dynamics or changes in the hull wake. A recommendation can thus be to initiate studies on how these guidelines can be updated to better reflect the real-life situation.

The previous results and discussion relate to predicted underwater radiated noise, being the objective of this project. However, also the pressure pulses on the hull were recorded both during the sea trials and the experiments and this data can complement the analysis. It can be considered a good proxy on whether cavitation dynamics are correctly predicted when the attempt to do actual observations failed. The comparison between the different data sets is presented in Figure 11. Here the levels at the first four blade passing frequency (BPF) harmonics are presented; the first BPF is at 6.3 Hz, also visible as a tonal in the CFD results in Figure 9, with the fourth then being 25.2 Hz. We can here see that the CFD computations in a large domain, both the model scale and full-scale results, agree quite well with the sea trial data. In this frequency range, the URN is dominated by machinery noise, but we can here confirm that the predicted cavity dynamics are quite well captured. Conversely, the experiments greatly underpredict the levels at the higher BPF harmonics, which is believed to be due to the intermittency in cavitation. For the simulations in the tunnel section, the blockage seems to amplify the predicted levels.

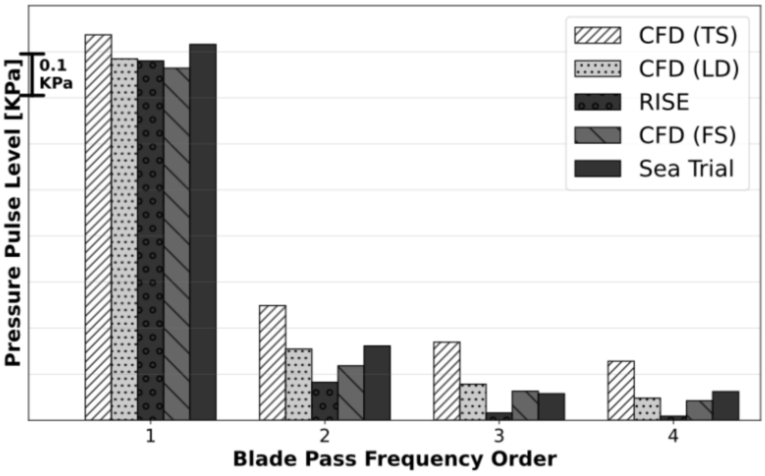
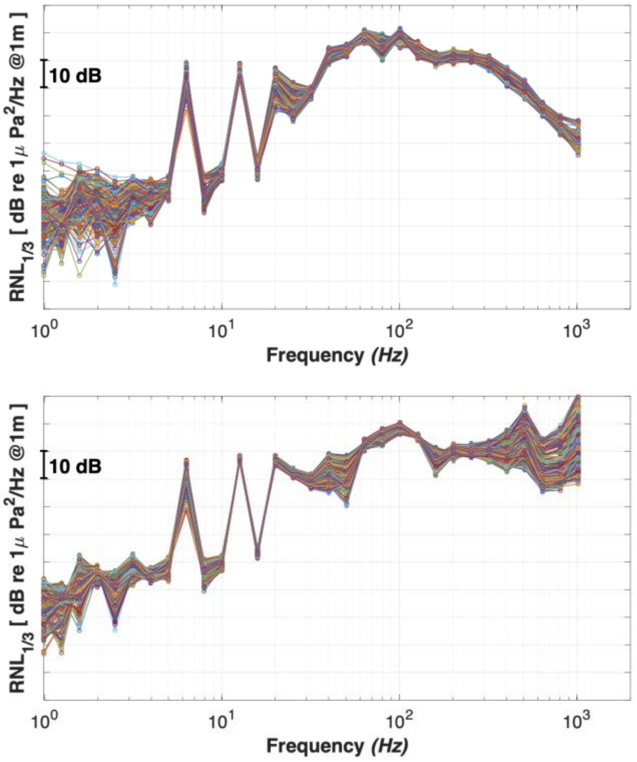


Figure 11 Pressure pulse levels at the Ahead transducer, comparison of sea trial measurements, model scale tests, and simulation predictions.

Comparing the new approach with the commonly used FW-H approach, rather similar predictions are made; in Figure 9 only full-scale results are included for the FW-H method. Except in a few frequency bands the results are within a few dB from each other.

Overall, it is clear that the set-up of the CFD computation influences results greatly. As been discussed, both in the predicted SL and the pressure pulses the effect of used domain size is shown to have a large impact. Not reported here, but discussed in Khraisat (2025), the mesh resolution used and how well the sheet and tip vortex cavitation is resolved is important. Finally, the application of the acoustic analysis through the FW-H method is sensitive to set-up choices of the permeable data surface. As noted above, the latter had been noted in previous research, and this formed the motivation for the development of the alternative approach. Simulations were nevertheless performed using the permeable FW-H method for comparisons and further investigations, and issues with the method were noted also in the simulations performed within PUB. As an example of this, Figure 12 shows the prediction for the three different surfaces tested (as indicated in Figure 6). Up to about 30 Hz, the predictions agree reasonably well, but for higher frequencies only the largest surface gives physically consistent results showing an expected decay in RNL in the high frequency range. The reason for this was found to be related to the standard computational method to deal with a rotating propeller that affected the smaller surfaces. One could then remark that it's generally recommended in literature to have a small surface. This indicates that the results then suffer a high risk to be contaminated. For more details, we refer to Khraisat (2025).



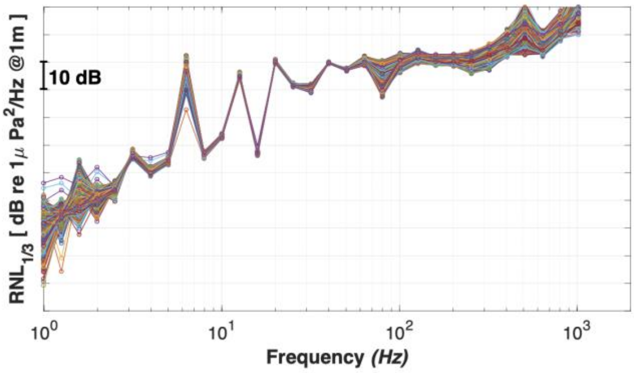


Figure 12 RNL from varying permeable data surfaces [5R (top), 2R (middle), and 1.4R (bottom)] for all receivers

6 Utilisation

The project was developed as an innovation project, with the awareness that the topic of URN is challenging and far from mature. Even though the results reported above show that the accuracy in predictions are not yet satisfying, the project has generated several results that have formed basis for further utilisation, both for industrial usage and for R&D projects on a higher TRL.

One example is the project InciteShip, funded by Trafikverket and coordinated by IVL and involving FOI and Terntank from PUB. There, a buoy system for continuously collecting signatures from passing ships is being utilized, with the intention to be used for monitoring of URN in shipping lanes and for integrating URN emissions into incentive systems. Experiences from the sea trials performed in PUB were used in the development of the measurement system. The system will further be used in PUB-TVÅ where data will be collected to analyse mitigation measures towards URN.

Another spin-off project is BOUB, also funded by Trafikverket and coordinated by Chalmers and involving KM and Terntank from PUB. In BOUB, the idea is to develop an onboard monitoring system for real time feedback to the ship crew on URN emissions. Simulation techniques and experiences from PUB will be used in this project.

The new method to predict URN from a CFD computation was shown to be more reliable than the traditional FW-H approach while yielding results of similar quality to a lower computational cost. The method is already implemented at KM and further evaluated for usage in commercial projects.

A final useful outcome of the project worth highlighting is the network developed between participating partners. We have through PUB developed a small but active community working with URN from shipping in Sweden with a high international recognition.

7 Concluding remarks

A glance at Figure 9 reveals that the project did not reach its intended goals. But despite that the discrepancies are large, the lessons learnt are also large and we have taken considerable steps forward to close the gaps. Some of the reasons for the varying results have been determined, and work is ongoing to identify further causes that could be remedied in future predictions.

In relation to other recent studies, it seems there is still no consensus on a method to do a fair comparison of SLs from different vessels. At the 2nd IMO workshop on URN and energy efficiency (IMO, 2025) several studies were presented on the effect on URN from both noise mitigation actions and energy efficiency measures that show very optimistic results and good agreement of predictions. In contrast, the Wageningen W2025 workshop on CFD in ship hydrodynamics (W2025, 2025) included a case on cavitation nuisance predictions, and the twelve contributions, from well-established organisation, showed a very large variation in predicted pressure pulses and URN.

One further study, performing CFD computations with transient ship wake dynamics captured using so called DES instead of RANS; methods that are too expensive for industrial usage but that we believe could give better predictions of broad band and high frequency content in the noise. The computations themselves will require too much resources to be used in design work, but the knowledge generated can help interpret the results from the more feasible RANS approach used in PUB. Further, continued analysis of the results and potential improvements of the cavitation tunnel experiments are being performed with further assistance from CFD.

We're confident that repeating the exercise of comparing sea trial data, experiments, and CFD would yield a better agreement, although certainly not yet a perfect match. The perhaps interesting usage, to do a relative comparison of different operating conditions or ship designs in the framework of evaluating URN mitigation measures will be part of PUB-TVÅ.

8 Publications

Andersson, C., Linné, M., Johansson, T., & Andersson, M. (2024). Measuring Ship Underwater Radiated Noise in Shallow Waters-Why Not in the Near Field? *Proceedings of the Institute of Acoustic*

Khraisat, Q. S. A. (2025). *Numerical Investigation of Scale Effects on Cavitation and Underwater Radiated Noise*. Licentiate thesis, Chalmers University of Technology.

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