Project Final Report for the
Transport Canada
Program to Address Disturbances from Vessel Traffic

Quiet Vessel Initiative

Hydrodynamic Propeller Noise Monitoring System - HyPNoS

Revision 1

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1 Executive Summary

The project *Hydrodynamic Propeller Noise Monitoring System – HyPNoS* has during the project duration and beyond contributed in achieving the objectives of promoting and verifying the effectiveness of retrofits, facilitating quieter ships with noise prediction methods and generating noise awareness among vessel operators. HyPNoS is the name of this research project as well as the live on-board underwater radiated noise (URN) monitoring system with a calibrated prediction algorithm with vibration hull data input. In the project two different propeller designs were compared, hydrodynamic simulations were performed and the HyPNoS was developed and commissioned. Three measurement campaigns created a wealth of underwater noise and vessel vibration data for an original and a noise optimized SCHOTTEL controllable pitch propeller design in the BC Ferries Coastal Class type vessels. Supporting numerical simulations of the hydrodynamic flow shed light on the of the noise emission characteristics and the hull vibration distributions. Both simulation and measurement data were used to develop an on-board system based on the SCHOTTEL MariHub condition monitoring framework, which applies an accelerometer on the hull above the propeller to measure vibrations. An AI-ready live algorithm based on the measurement and simulation data was developed to correlate the instantaneous measured vibrations with the underwater measured noise. The new software was implemented in MariHub and commissioned on the BC Ferries Coastal Class vessel with optimized propellers and tested in a final measurement campaign to assess the performance of the system. Public outreach of the project results has been achieved by maintaining a strong presence online and on technical conferences and is still ongoing for up to 6 months after the project termination. The intention is that the URN monitoring system can be rolled out to the two sister vessels as well.

2 General Description of the Project Major Achievements

2.1 Major Achievements

The many major achievements within the project can be categorized into four aspects, which are listed in the following with their respective approach:

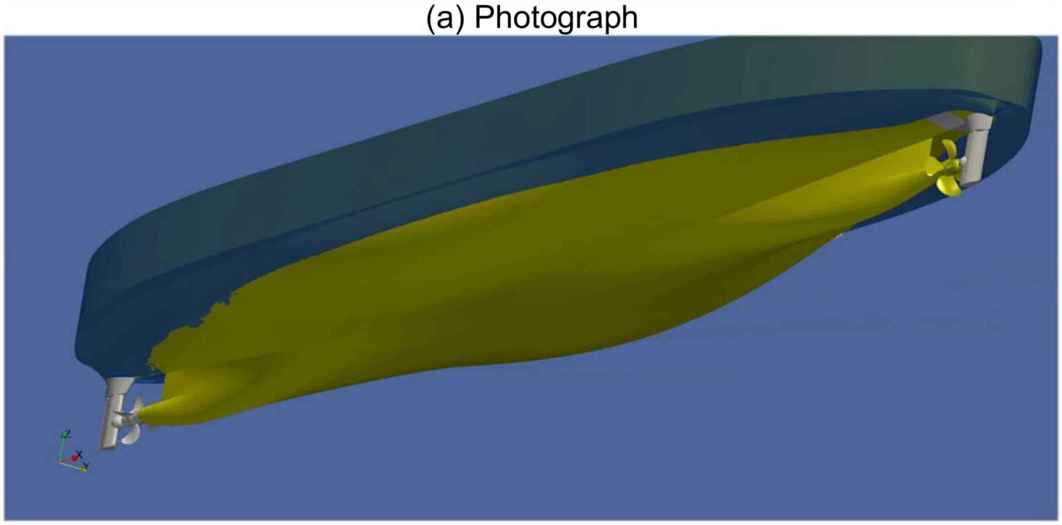
1. **Underwater radiated noise prediction tools**
   → High-fidelity hydrodynamic numerical computational fluid dynamics (CFD) simulations
2. **Field tests and trials**
   → Well trained engineers with high repeatability processes and high accuracy equipment
3. **Software of the noise monitoring system**

→ AI-ready live cloud based generic algorithm with vessel borne sensor array

4. **Dissemination of the project results**
   →Web based and technical conference outreach

The target case for this project was the BC Ferries Coastal Class, a $L_{wl} = 159m$ double ended RoRo passenger ferry with a width of $B = 27.4m$ and a draft of $T = 5.3m$. There are three identical sister vessels, the INSPIRATION, CELEBRATION and RENAISSANCE, which are consecutively and in that order equipped with an updated propeller design during the project duration and beyond at their respective quarter life upgrade dockings. In Figure *1* (a) the target case vessel is shown with the 3D-model in (b) that is geometrically discretized for the simulations with the water surface extracted from a precursor simulation.

(a) Photograph



(b) 3D-model for numerical domain

Figure 1: HyPNoS Target case

The first aspect of this project is the URN prediction with engineering methods. The final predictive simulation results for the noise optimized propellers are given in Figure *2* together with the experimentally obtained signature. While the characteristics of the two narrowband spectral representations seem different the maximum values are in good agreement. It seems that there is some additional noise in the measurement that is masking the detailed spectrum shown by the purely hydrodynamic simulation. This might be attributed to machinery or other on-board noise, or environmental influence such as reflections or third party traffic that was not directly observed or reported by the measurement team. The characteristic frequencies such as the blade passing frequency and its higher harmonics given in magenta in the graph are well predicted by the simulation, while they do not appear in the measurement at all. In addition there are several sub harmonics and higher harmonics visible in the simulation result. A numerical issue is the possible cause for the high amplitudes at the upper frequency end. Considering the Nyquist frequency, the upper frequency limit was set to $f_{Nyq} = 4kHz$ in the simulation due to the resource limitations.

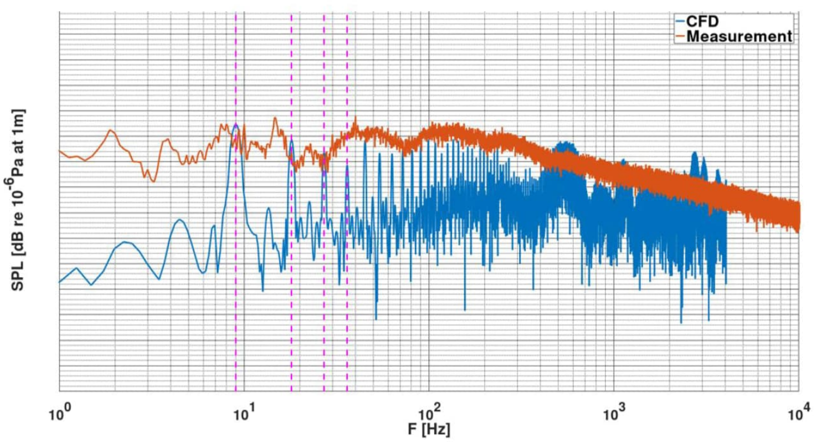


Figure 2: Validation of simulation results

The second aspect is the measurement and processing capabilities regarding on-board vibrations and URN. The vibration data was evaluated with 12 sensors, 8 in hull normal direction and 4 in hull parallel direction with great success. All sensors showed very similar vibration data. With the training received as part of this project and the new measurement equipment, SCHOTTEL is able to achieve a higher repeatability of URN measurements and a good agreement with the values of the permanently installed sensor arrays. In Figure *3* the spectrum from the 2. measurement campaign in blue, which is the calibration measurement for the system, is compared to the 3. campaign in yellow, which is the validation measurement for the system. In green the JASCO measurement at the boundary pass hydrophone test track from the 1. campaign experiences a maximum at $f = 80Hz$. While the propeller blade frequency is at $f = 9Hz$ it may be at a frequency that is often caused by cavitation or in this case the interaction of the propeller slipstream with the rudder. Therefore it is not conclusive, if it is propulsor noise. The JASCO data was only available in 1/3 octaves, which prevented further analysis of the source of the discrepancies.

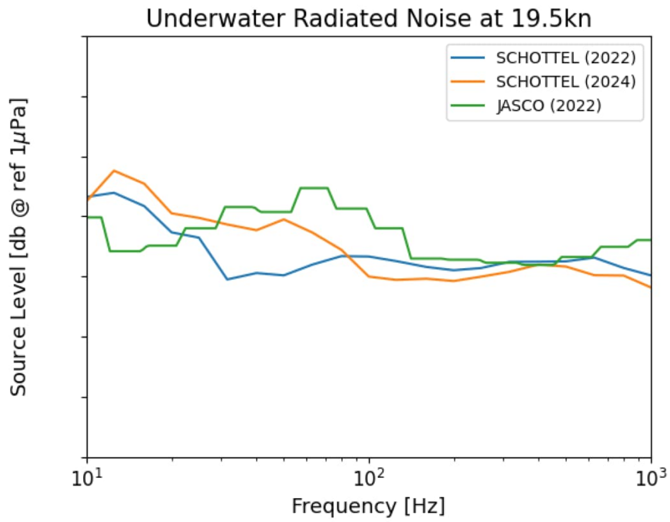


Figure 3: Measuring quality: repeatability and comparison to fixed installations

The original and noise optimized propeller design for the vessels is experimentally obtained in the field and compared in Figure *4* for the vessel speed of $v_s = 20kn$. A clear reduction of the acoustic emissions is visible in the subharmonic ranges as well as the low and high frequencies below $f < 9Hz$ and above $f > 1.5kHz$ with reductions between 5 and $10dB$. Surprisingly the propeller blade harmonics are not distinct in the measurement at all for all measurement data sets and in this case there is no significant reduction of noise at the blade passing frequencies. This is in strong contrast to the numerical simulations, where the propeller blade harmonics are the dominating feature of the under water noise signature.

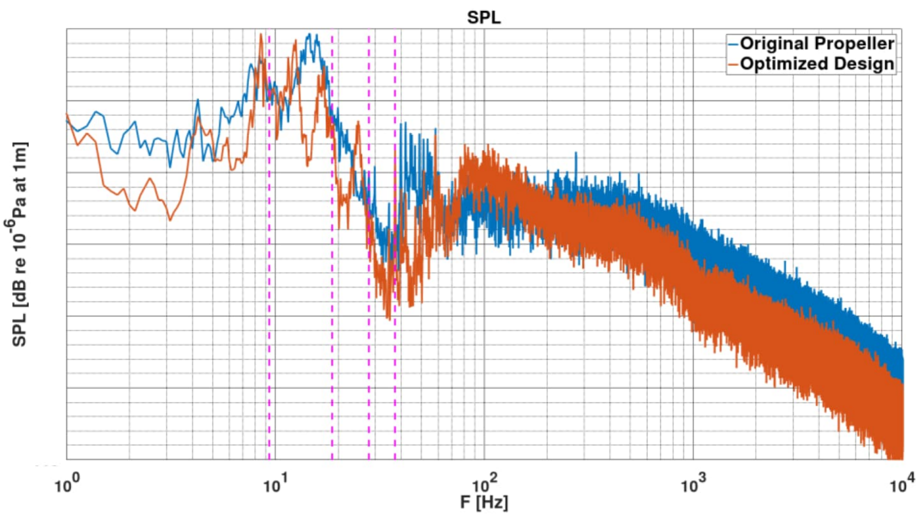


Figure 4: Experimental comparison of the original and noise optimized design

The 3. and main aspect of the project is the live on-board prediction software, which is developed, commissioned and tested in the field with great success. A well fitting cross correlation between the different data types of onboard vibrations and far-field noise has been proven for different operation points in Figure *5* for the overall sound pressure level (SPL) of the URN values. The wealth of measurement data from the 2. measurement campaign is shown in red, while the final prediction of the algorithm is shown in blue with the lines showing the least squares data fit. A simple and stable correlation method is used for this prototype, however, the software solution allows a generic implementation of any algorithm for prediction and machine learning tools were tested on the system within the project. In combination with a cloud based URN evaluation and user interface, the system can be considered AI-ready. From the generated URN database it may be possible to generate training data for artificial neural networks in the future.

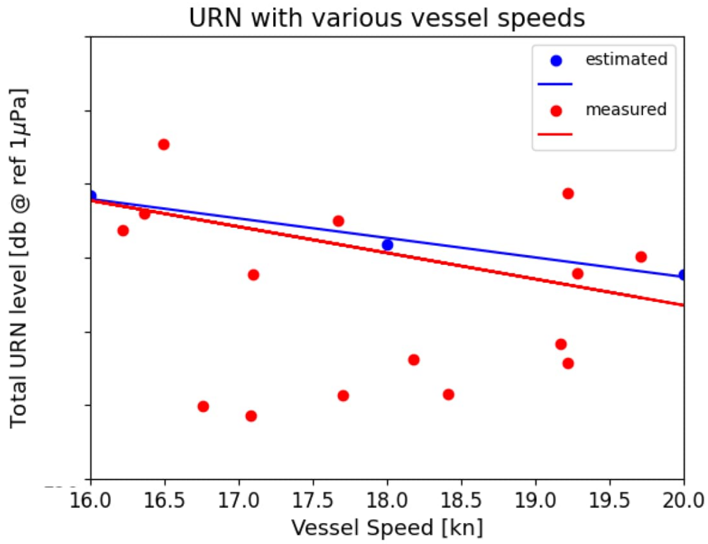


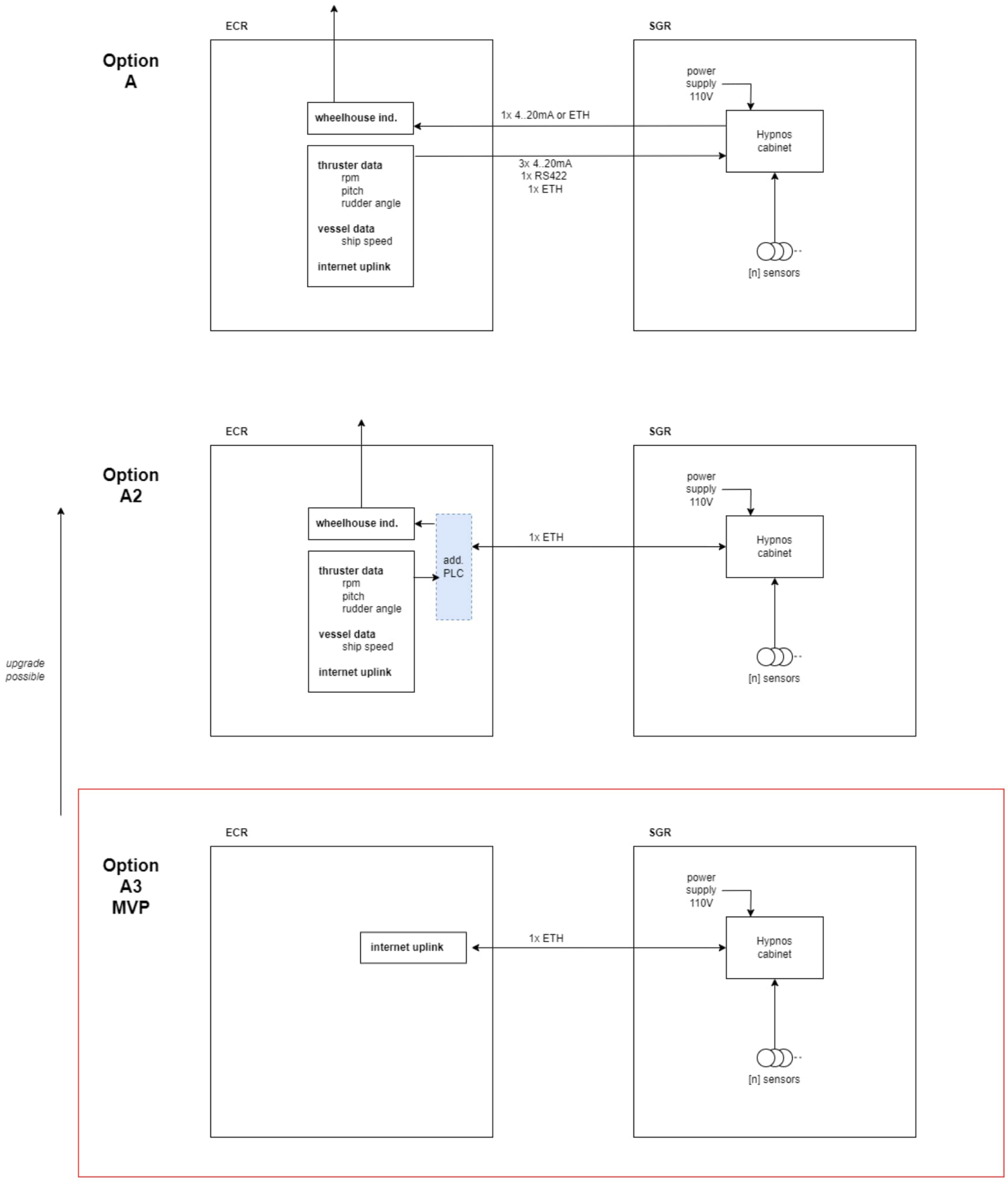
Figure 5: Final prediction quality of the live on-board algorithm

2.2 Activities and Timeline

Work Process 1

Work process 1 was established for meetings, reporting and dissemination. There have been a number of meetings with BC Ferries regarding the organization of the project and the measurement campaigns. In multiple meetings the installation of the HyPNoS live monitoring system was discussed as there was no way install new cabling outside of the quarter life upgrade. Unfortunately, the quarter life upgrade of the INSPIRATION was before the project and the quarter life upgrade of the CELEBRATION, which was originally scheduled to be during the project was moved to May 2024. As it was not possible to extend the project duration, the system had to be installed with the available cabling, which resulted in sub ideal options summarized in Figure *6*. The steering gear room (SGR) is the location, where the acceleration sensor array is to be positioned and the engine control room (ECR) is the location with the system uplink to the BC Ferries operated network. The connection in the ECR is required to obtain the measured data in any way during operation, as the SGR can not be accessed during vessel operation. The main difference between the options A and B is the location of the switch board cabinet that contains HyPNoS, where the sensor data is evaluated. If the cabinet is located in the ECR, option B, it can process the data from both ends of the vessel, however, it was not certain, that the sensor data can be transferred with sufficient accuracy along the existing ethernet cable over long distances. The only possible solution was therefore option A and due to limited workload available from BC Ferries at that time the minimum possible solution was selected as A3, where the sensor data is processed in the SGR and sent via internet uplink to the cloud, where BC Ferries may access it from any internet capable device. There were more internal meetings at SCHOTTEL to coordinate measurements and exchange results from the three work processes.

SCHOTTEL was delighted that there was minimal reporting necessary to Transport Canada, which kept the overhead small meaning more resources could be allocated to research work. There has been reporting activity for the 1 year progress report and after the project duration for this final report.


Option A
ECR
SGR
wheelhouse ind.
thruster data
rpm
pitch
rudder angle
vessel data
ship speed
internet uplink
1x 4..20mA or ETH
3x 4..20mA
1x RS422
1x ETH
power supply 110V
Hypnos cabinet
[n] sensors
Option A2
ECR
SGR
wheelhouse ind.
add. PLC
thruster data
rpm
pitch
rudder angle
vessel data
ship speed
internet uplink
1x ETH
power supply 110V
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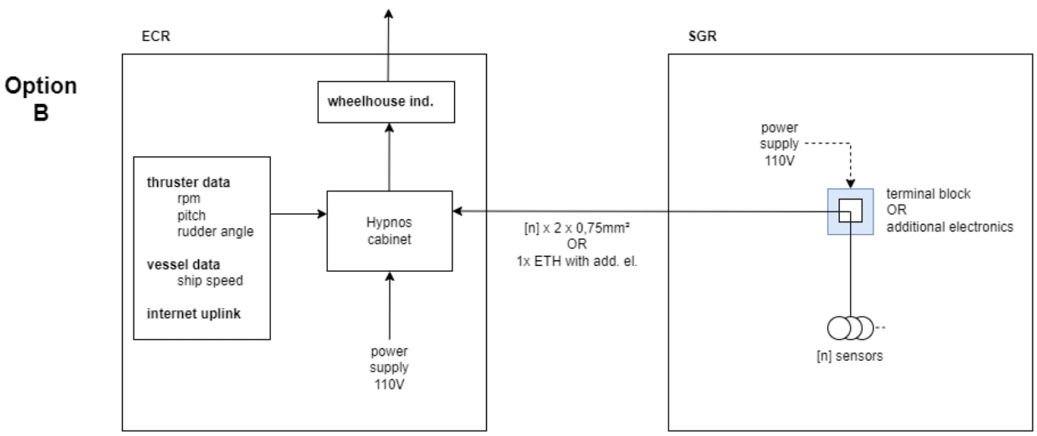


Figure 6: Options for installation without quarter life upgrade

Dissemination activities as part of this work process include:

- 4x LinkedIn Posts
- 2x Press release
- 3x Conference presentation
- 2x Scientific journal publication
- 1x Magazine publication (organized by Transport Canada)

The target audience for the dissemination of results are researchers, vessel owners, vessel operators, GOs and NGOs, competitors and port authorities. In particular ferry operators and vessel owners in regions of current or future implementation of environmental restrictions could be interested in the findings and the resulting technology.

The first press release was published on the SCHOTTEL website in November of 2022 (https://www.schottel.de/en/media-events/press-releases/press-detail/schottel-selected-for-funding-under-transport-canadas-quiet-vessel-initiative), in combination with a LinkedIn post by the official SCHOTTEL channel. While the LinkedIn post aims to inform the general public about the existence of the project and the possibility reduce vessel noise by adjusting propeller design and operational practices, the website goes into more detail regarding the collaboration of SCHOTTEL and Transport Canada and lists the work items within the project. To the knowledge of SCHOTTEL the press release was used in different national and international maritime magazines for instance in:

- Schottel erhält Förderung von Transport Canada - Schiff&Hafen (https://www.schiffundhafen.de/nachrichten/schiffbau/detail/schottel-erhaelt-foerderung-von-transport-canada.html),
- Schottel selected for Quiet Vessel Initiative - Diesel & Gas Turbine Worldwide (https://www.dieselgasturbine.com/news/schottel-selected-for-

quiet-vessel-initiative/8023969.article),
- SCHOTTEL Selected for Funding Under Transport Canada's QV Initiative (https://www.maritime-executive.com/corporate/schottel-selected-for-funding-under-transport-canada-s-qv-initiative),
- Quiet vessel initiative: Schottel entra a fare parte dello studio canadese (https://marinecue.it/quiet-vessel-initiative-schottel-entra-a-fare-parte-dello-studio-canadese/31797/)

In addition, a section about all publicly funded research projects is released in March 2023 on the SCHOTTEL Website, which also features a short overview of the project. (https://httschottel.de/en/about-us/engineering/research#hypnos)

The project was presented at the Canadian Ferry Association Conference and Trade show in September 2023 in Vancouver, British Columbia, where Transport Canada was also invited. SCHOTTEL was a gold sponsor, which is associated with a technical session slot. For this presentation the HyPNoS project is selected to present experimental results and preliminary findings for the noise prediction algorithm. This presentation detailed the preliminary CFD simulations, the measurement campaigns and an outlook on the capabilities of the algorithm. The outreach was roughly 200 people from a number of shipyards, design offices and operators. At the Schiffbautechnische Gesellschaft Haupversammlung November 2023 in Bremen Germany the project was showcased as part of a presentation on underwater radiated noise capabilities of SCHOTTEL, which was accompanied by a publication of the paper “Evolution of Underwater Noise Emission Prediction Technology for Ship-Propulsor Combinations in an Industry Environment” in the journal Ship Technology Research – Schiffstechnik, which is scheduled to be released in November 2024 for the next Schiffbautechnische Gesellschaft Hauptversammlung. The abstract is given here:

> *“The prediction of underwater noise emissions by marine vessels has evolved significantly over the last decade as the interest shifted from exclusive military to civil use as a result of environmental concerns. Among different research groups best practices for the estimation with high-fidelity simulation methods based on hydrodynamic sound emissions are developed considering the complete vessel and propulsor. Here the current state-of-the-art computational fluid dynamics (CFD) approach, centered around propulsion units, is worked out in steps leading to the application for vessels. This consists of incompressible finite volume method flow simulations with large eddy turbulence modelling and volume-of-fluid phase capturing with a Schnerr-Sauer cavitation model in combination with an added permeable surface Ffowcs-Williams-Hawkings method for far field acoustics. Many mechanistic arguments support it and the final validation cases lead to acceptable accuracy and enrich simulation data acquisition,*

however, few technical limitations reveal weaknesses compared to traditional approaches."

The outreach of the conference presentation was about 60 people, consisting of operators and shipbuilding students and an expected 1500 people consisting of designers, yards and operators as well es government or NGO key personnel with the research article published later. The final presentation as part of the HyPNoS research project will be at the BC Tug Boat Conference in May 2024, which will introduce the developed system to other markets that may develop interest in noise monitoring soon as a result of the stricter guidelines on the reduction of URN by the IMO. This show has an expected outreach of 100 people which consist of yards, operators and owners.

An open access research paper is planned to be published online with the publisher MDPI in the Journal of Marine Science and Engineering. The article is then published under the Creative Commons Attribution License to be permanently available, which will greatly increase the outreach. The exact number cannot be estimated, but due to the exclusivity of full-scale measurements should be well over 5000 unique accesses in the first 5 years. This is scheduled to be submitted in July of this year and possibly published by Fall 2024. The paper will highlight the algorithm and its prediction capabilities as well as the data basis. The publication of the article will be posted on the SCHOTTEL LinkedIn channel.

Transport Canada organized another dissemination activity in collaboration with Clear Seas, which is planning to publish all Quiet Vessel Initiative project results in a 4 series article. Depending on the article contents, it may be referenced in a SCHOTTEL LinkedIn post. The project conclusion after this report will be published with a final press release on the SCHOTTEL website and accompanied by a LinkedIn post. If the results from this project eventually lead to a SCHOTTEL product, the outreach will continue, however, this will not be connected to the HyPNoS research project anymore and only may mention the project as the origin of the product.

Work Process 2

In work process 2 state-of-the-art numerical hydrodynamic simulation are performed, the setups are improved and the results are evaluated to support the development of the HyPNoS live prediction algorithm. The hydrodynamic underwater noise prediction with computational fluid dynamics simulations was advanced significantly during the project, in which the vessel was simulated at design speed of $v_s = 19kn$ and a rotation speed of $n = 135rpm$. The two propeller designs at the design pitch were simulated, which are compared in Table 1, with one being installed initially as the original design and one fitted at the quarter life upgrade of the vessels as an URN optimized design. For the simulation the front unit is in full feathering mode, meaning the resistance is minimal and there is no rotation.

Table 1: Investigated Coastal Class propeller designs

	Quantity	Unit	BCX-30	BC4724_1
Type	–	–	„Original“	„Optimized“
Diameter	D_P	m	5.0	4.7
Area Ratio	A_e/A_0	–	0.581	0.638
Pitch	$P/D_{0.7}$	–	1.113	1.213
Skew	φ	°	26.9	29.7
Number of blades	z	–	4	4
Rotation rate	n	Hz	2.25	2.25
Design Power	P_{in}	kW	11000	6820
Design Speed	v_s	kn	22.0	19.2

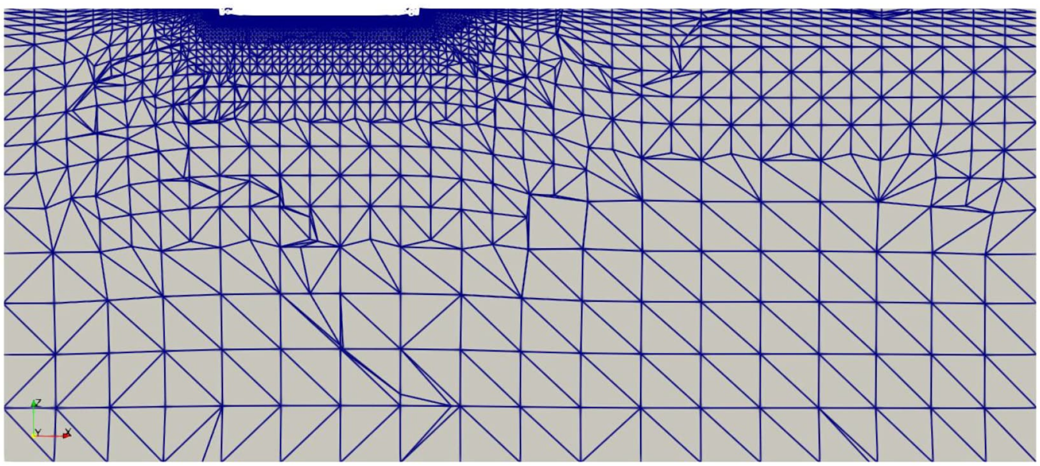
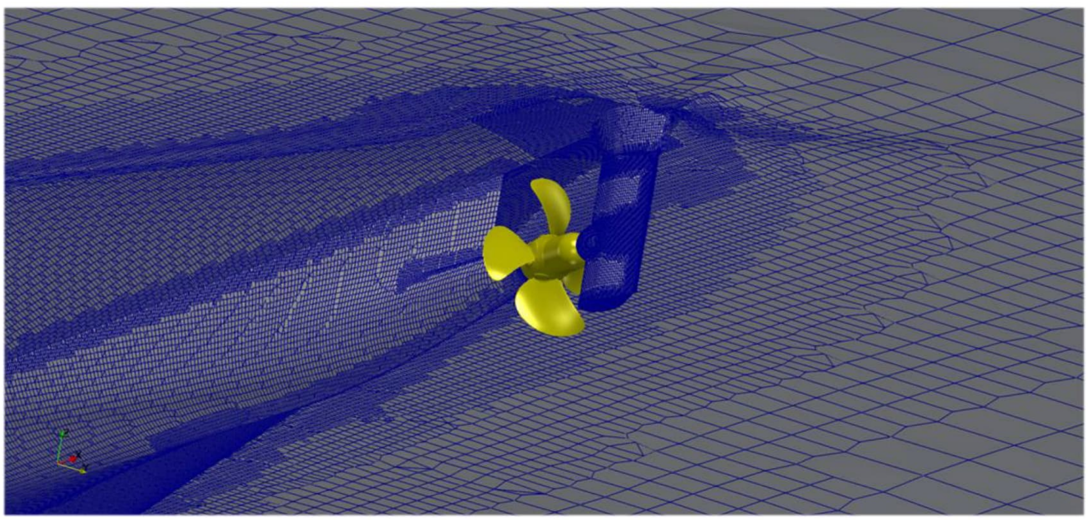
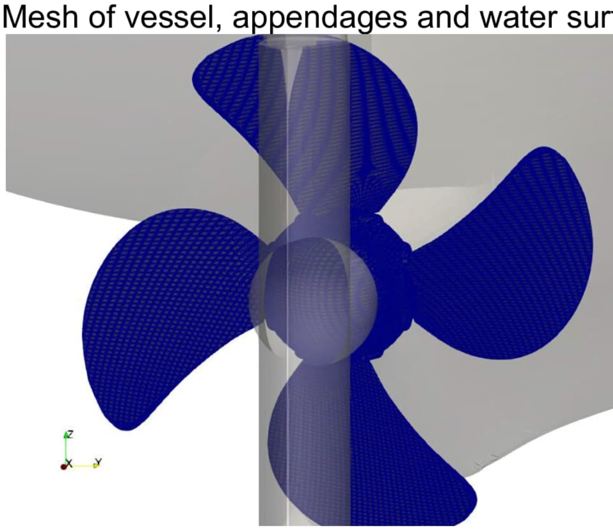


Figure 7: Slice of finite volume mesh at centerline

The finite volume method hydrodynamic simulations with two-phase cavitation prediction and Large Eddy Simulation (LES) turbulence modelling with a Ffowcs-Williams Hawkings acoustic analogy have been finalized to reveal the URN signature at realistically placed hydrophone observers and the hull vibrations at the vessel surface area of interest, where vibration sensors were placed in the measurement campaigns. For these simulations the HELYXcore version 3.3.2 OpenFOAM distribution from Engys Ltd. is utilized with an incompressible, isothermal two phase homogeneous Eulerian mixture solver interPhaseChangeDyMFoam where the cavitation is modelled with the OpenFOAM Schnerr-Sauer cavitation model. The vessel is simulated at a typical operation point of $v_s = 19kn$ taken from the second measurement campaign for the original propeller design. Geometrically the vessel is placed in a quasi infinite domain and a water depth equivalent to the location of measurement of $360m$. A slice of the mesh is given in Figure *7* and the discretized surface geometries in Figure *8*, where the water depth is considered and a water surface taken from an independent resistance simulation with a two-phase air-water free water surface representation. The vessel, appendages and water surface in (a) have a relaxed target non-dimensional wall normal resolution of $y^+ \approx 300$ with 7 layers, whereas the propeller is correctly considered for LES with a wall resolution of $y^+ \approx 1$ and 10 layers. The total mesh size is approximately $27 \cdot 10^6$ cells with 1.3 Mio surface cells on the propeller. Note that the mesh above the propeller in the interrogation region for the vibration measurements is refined to a higher level. The dynamic propeller rotation is considered with a sliding mesh interface. The origin of the coordinate system is the intersection of the propeller plane with the shaftline or rotational axis with the x-axis pointing against the direction of travel of the vessel and the z-axis against the gravity vector. The propeller rotation direction is negative with respect to the x-axis and clockwise as seen from the aft in the direction of travel of the vessel.



(a) Mesh of vessel, appendages and water surface



(b) Mesh of propeller

Figure 8: Finite volume mesh surface geometries

The considered converged wave pattern in calm sea obtained with the two phase solver interFoam of the resistance simulation without aft propeller is shown in Figure *9* showing moderate wave heights. Note that slamming as a dynamic movement of the wave pattern is not considered in the final simulation as this is a steady state converged solution and it would be technically not feasible to consider a moving mesh at the water surface. As a result the hull above the front unit shows minimal wetness and the hull above the aft propulsor is just wetted at the interrogation region. A relevant simplification is the non-working propeller in the resistance simulation, which possibly leads to a slightly overestimated wave pattern height above the unit.

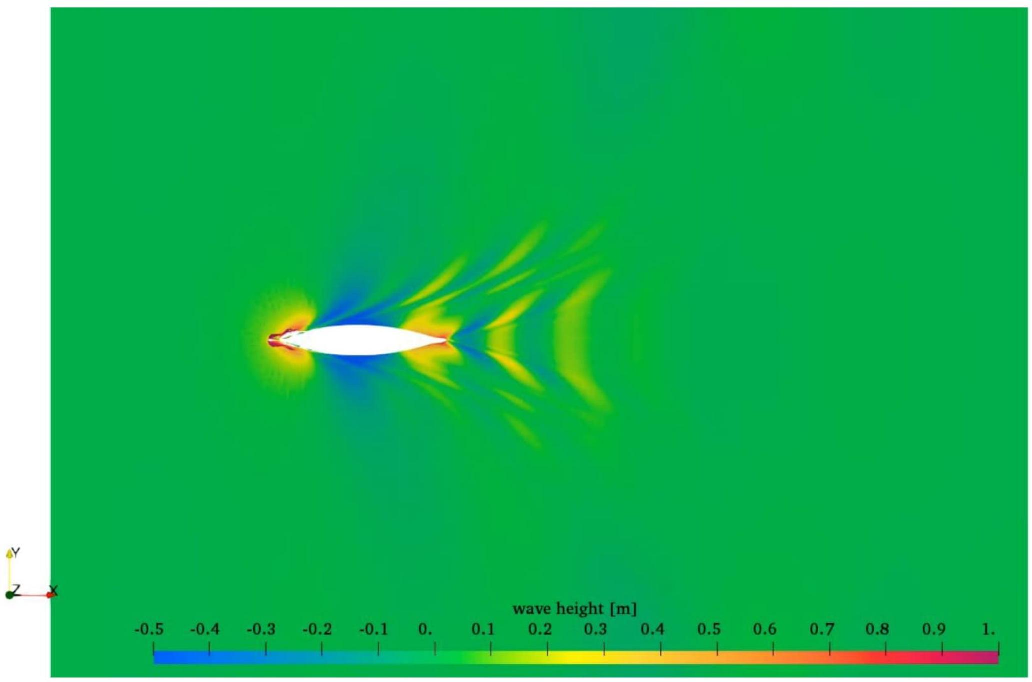
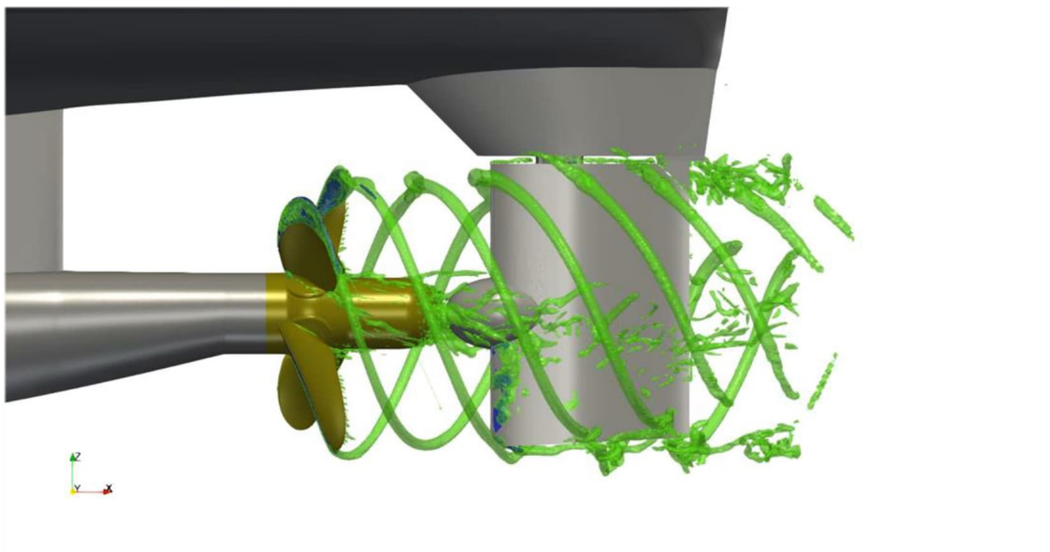
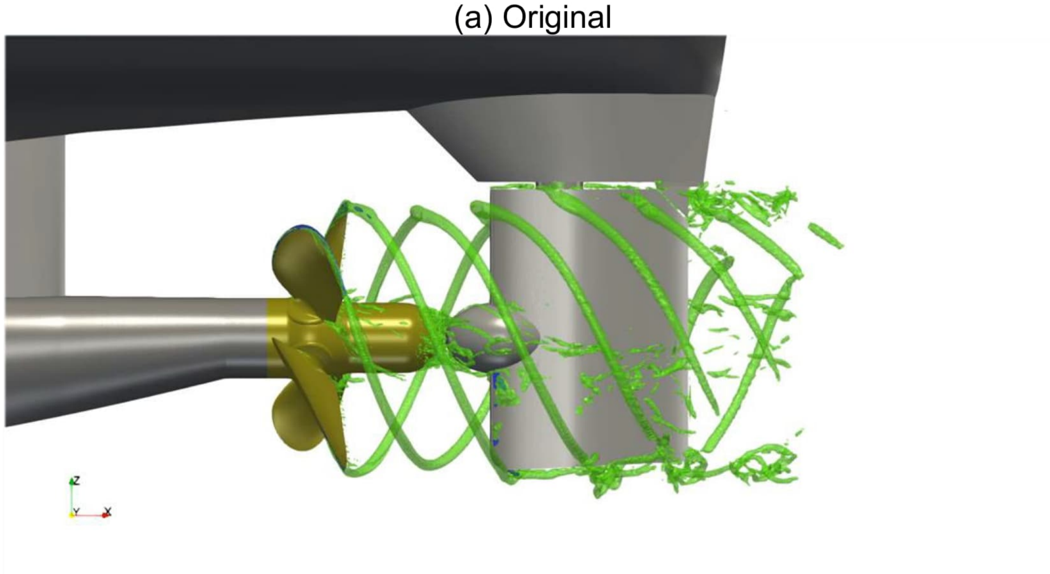


Figure 9: Wave pattern from resistance simulation

For the noise optimized propeller the documented pitch from the measurement in the field is set in the simulation, while the original propeller uses the design pitch leading to stark differences in the calculated power consumption with one third higher power for the optimized design and double the power for the original design compared to the measurement. A quantitative overview of the flow field for both propeller designs is shown in Figure *10*, where the $Q = 1000s^{-2}$ isosurface in green illustrates vortices and the $\alpha = 0.5$ isosurface in blue indicates regions of water vapor. There is a strong propeller slipstream deformation at the 12o'clock propeller position caused by the wake deficit from the sharp aft section. This creates a cavitating tip vortex slightly downstream of the propeller plane, which remains stationary in the wake deficit as the propeller blade tip rotates away. At the rudder lower leading edge or the rudder suction side in the propeller slipstream some rudder cavitation is visible. Despite the change in diameter both cases have an interaction of the tip vortex with the rudder gap and the rudder end, where the tip vortex is bursting into smaller turbulent structures. The three above mentioned effects are detrimental regarding noise sources, however, a clear improvement between the original design and the optimized design is visible despite the higher area load as a result of the smaller diameter.



(a) Original



(b) Noise optimized

Figure 10: Instantaneous vortices (green) and cavitation (blue) at a simulation timestep

The signatures of both propellers at the observer next to the vessel at the closest point of approach are given in Figure *11*. Across the complete frequency range the noise optimized design shows improvements of 2 to $10dB$. The first four propeller blade frequency harmonics are indicated with the dashed vertical lines in magenta. During the acoustic simulation run a timestep of $\Delta t = 0.1°$ is used, leading to a bandwidth of $f = 0.25Hz$ in this narrowband representation. Comparing this to the respective measurements in Figure *4*, there seems to be a strong contrast between the two. While the CFD simulations experience distinct high amplitudes in the signal at the propeller blade frequencies indicated with magenta vertical lines, this expected shape is not seen in the experiment.

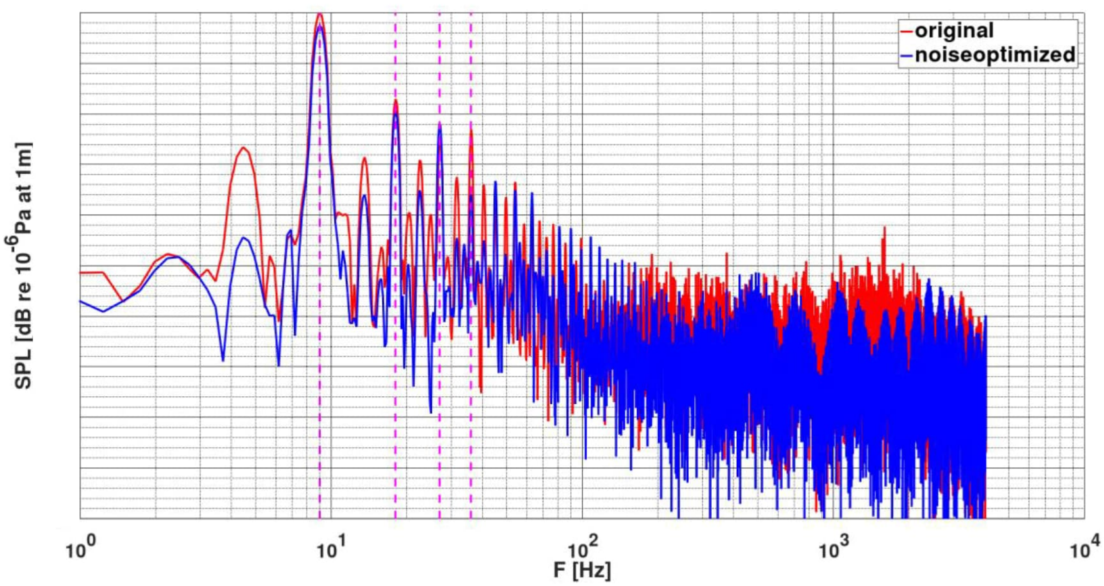
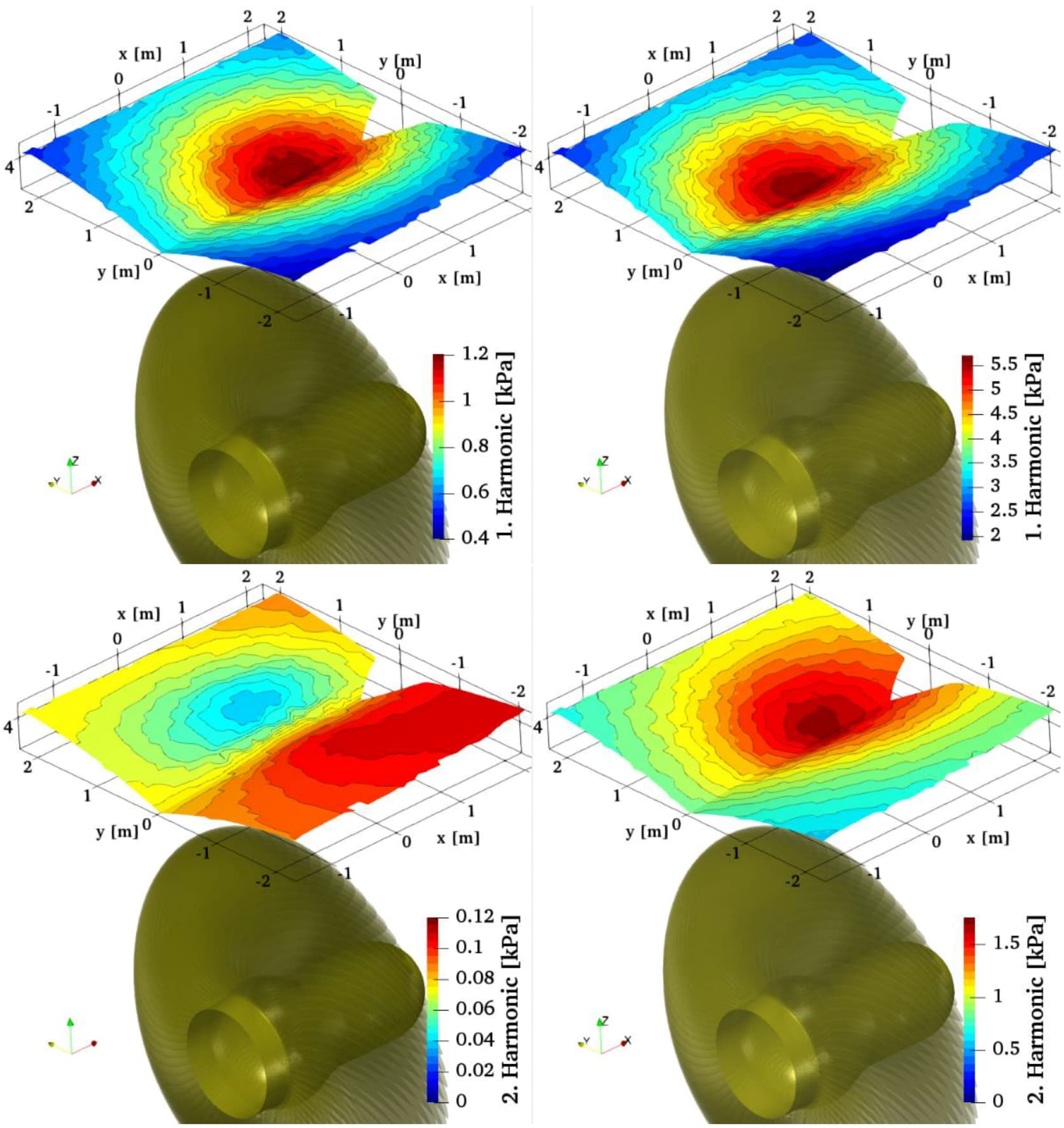
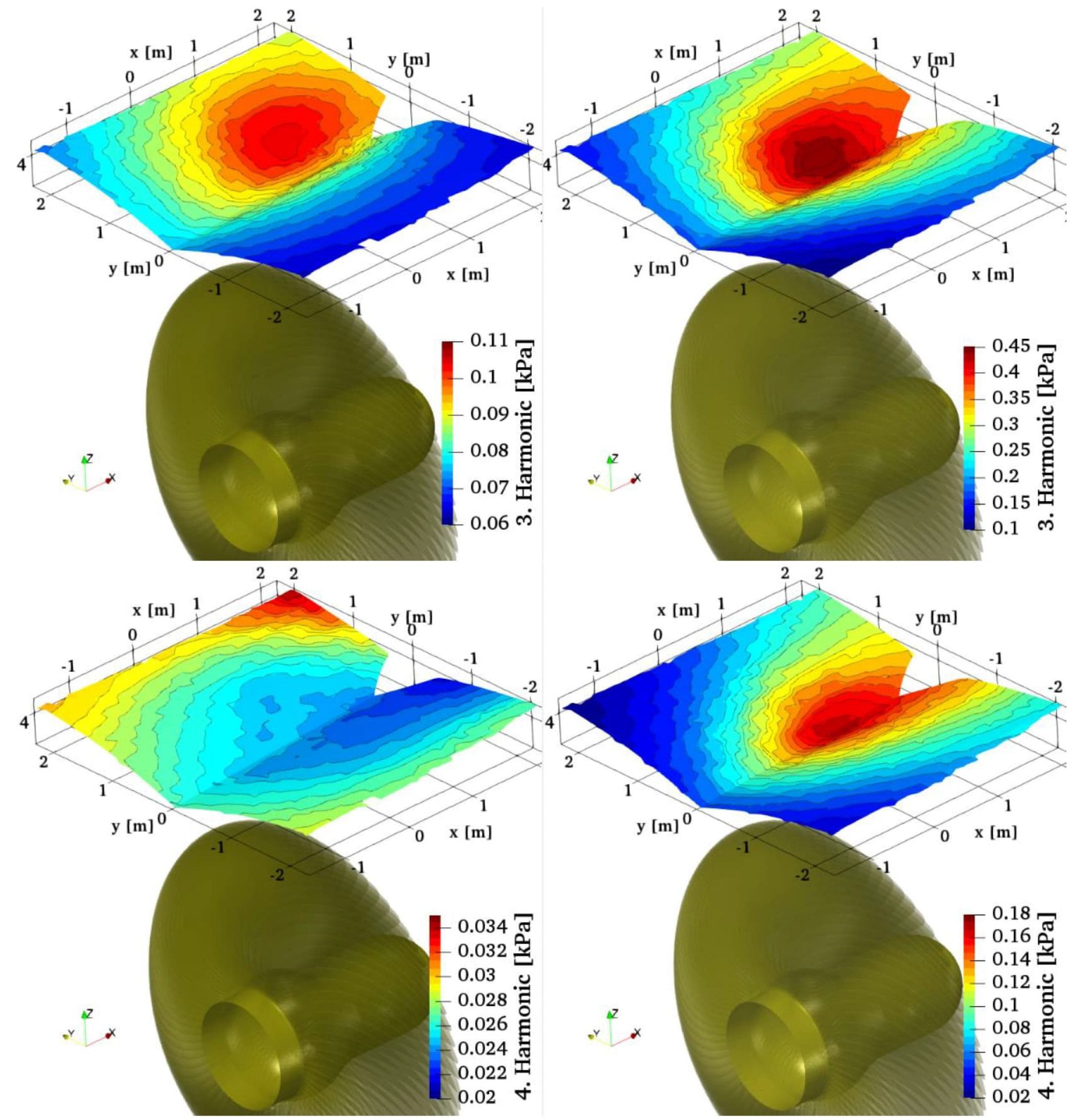


Figure 11: URN signatures of both propellers at the simulated operation point

For the placement of the vibration observers the vessel boundary patch above the propeller has been evaluated in detail regarding pressure pulse distribution and harmonic phase angle at the first four propeller blade frequencies and with a proper orthogonal decomposition of the complete data set. The pressure distribution is given in Figure *12* with the optimized design in (a) and the original design in (b). At the first propeller blade harmonic the original design has significantly higher pressure amplitudes, which stem from the increased propeller diameter and larger suction side sheet cavitation at the 12o'clock position of the blade with an additional factor being the increased amount of tip vortex cavitation. The pattern on the other hand experiences high similarity between both designs despite their completely different propeller geometries. This is a great advantage for the sensor system, as the propeller design seems to have minimal impact on the distribution of the maxima and thus the sensor amount and locations. At the second harmonic there is a developed asymmetry, which seems to be minimal just starboard side of the vessel centerline. For the third harmonic there is an equal pattern for both propeller designs, however, the center moves negligibly between the two cases. The observations at the second and third harmonic may be attributed to the difference between the dynamic cavity topology at the upwards and downwards rotating blade. For the fourth harmonic the observation is not conclusive as the value range for the optimized design is too low, to yield interpretable data regarding the pattern.

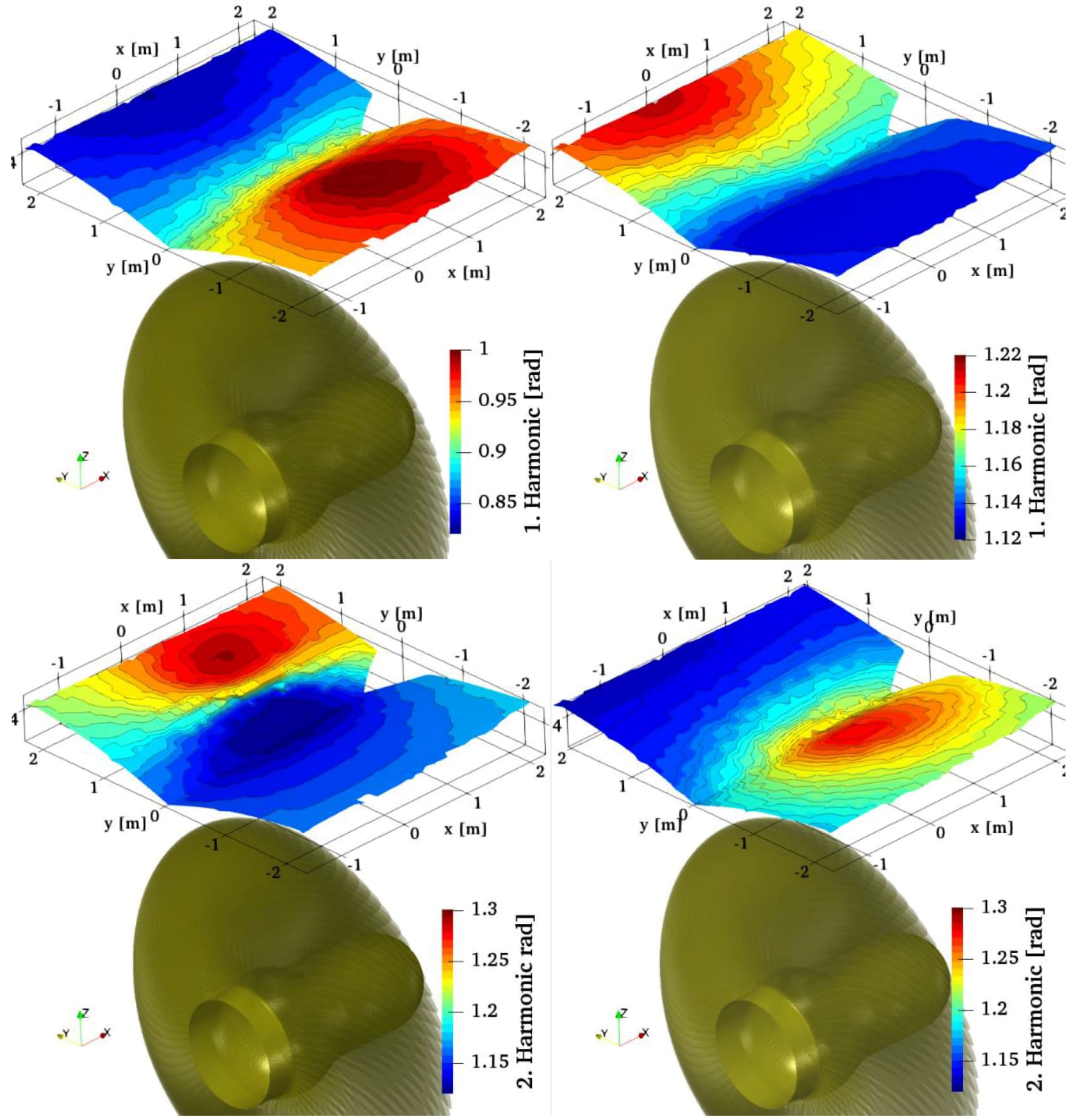


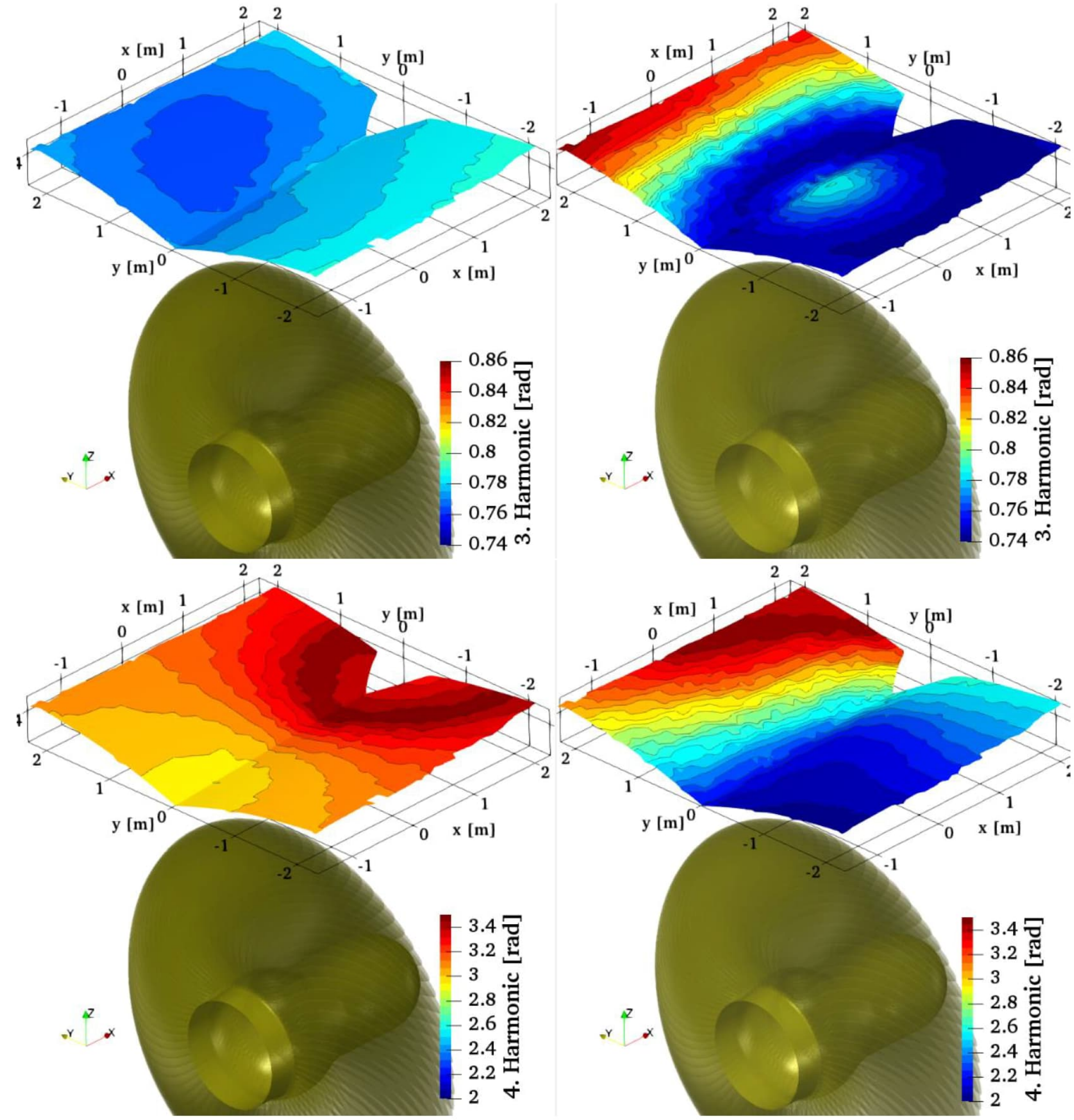


(a) Noise optimized (b) Original

Figure 12: Incompressible hull pressure pulse amplitudes at the first four harmonic frequencies from the FVM simulation

The phase angle distribution in Figure *13* with a value range from $-\pi < \varphi < \pi$ proves that phase shifts on the surface are minimal. With a maximum range of about 3% among the entire range for the first harmonic for example, the spatial phase information may be neglected for the sake of simplicity in the development of the algorithm. Comparing the propeller designs in subfigure (a) and (b), the distribution at the first and second harmonic are rather similar considering that the values may be additively inverted at will. The third and fourth harmonic on the other hand experience a distinctive difference, which may be attributed to the generally low excitation of the optimized design at these frequencies and thus different source characteristics as the source is not exclusively limited to the propeller.

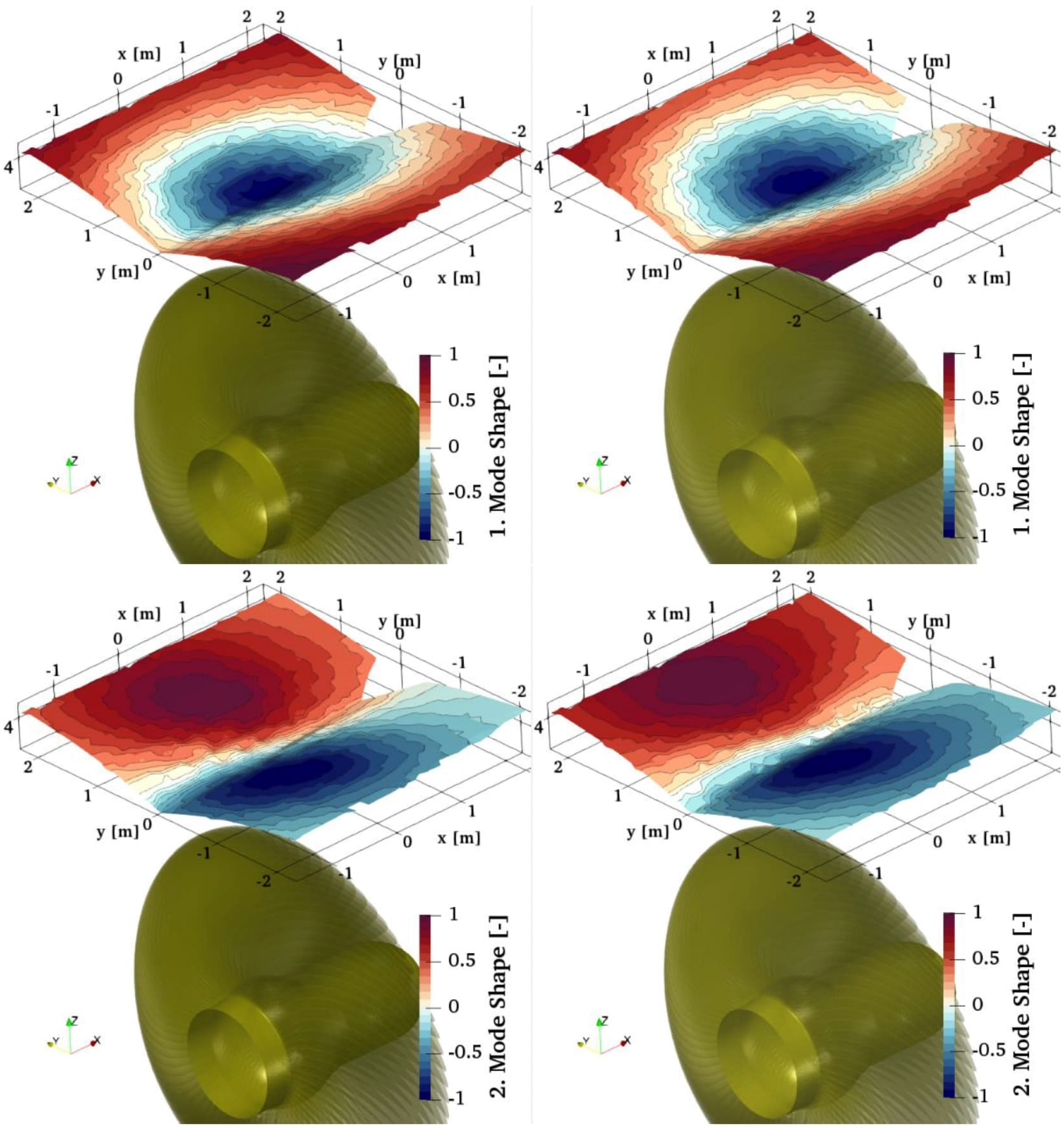


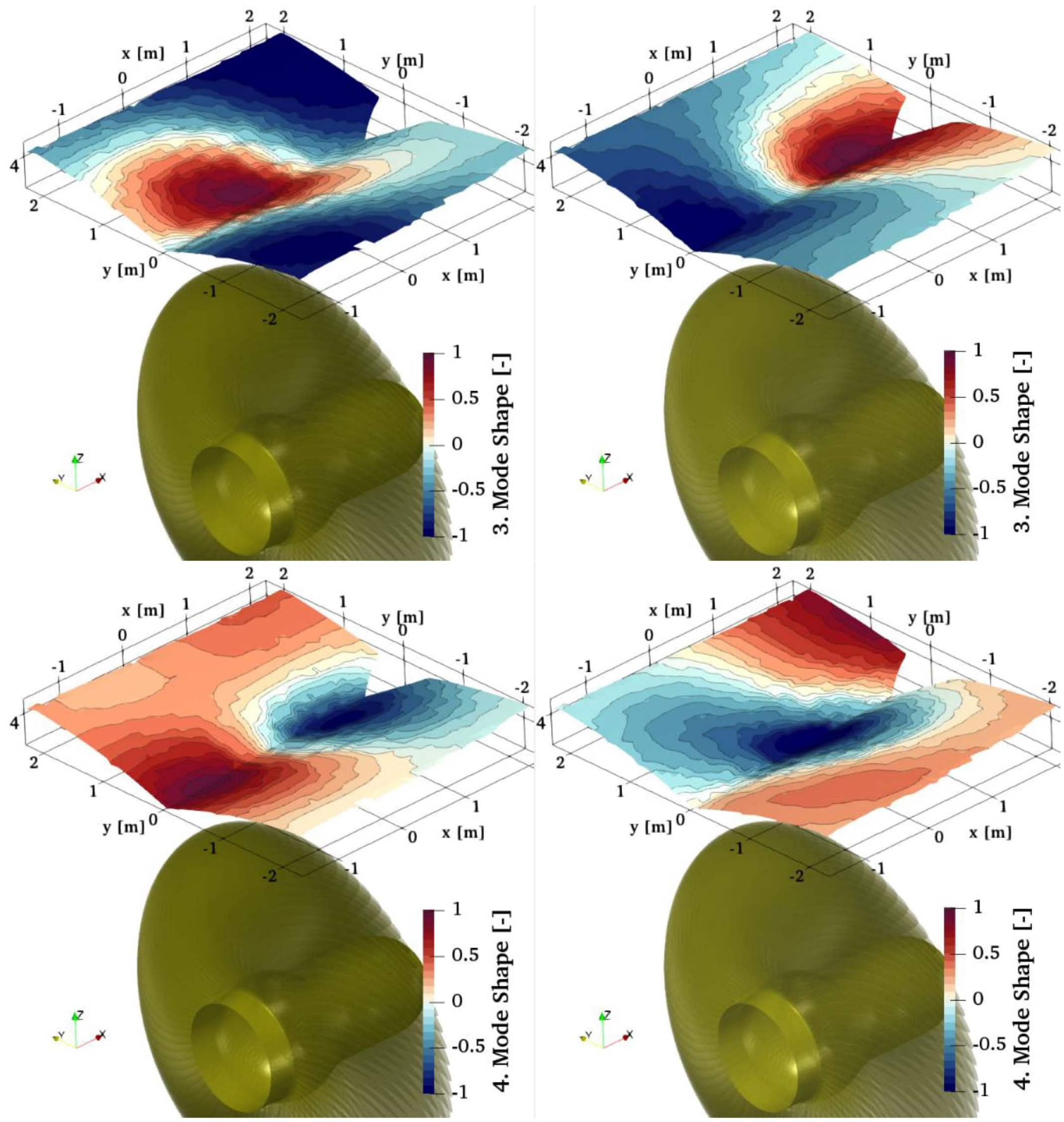


(a) Noise optimized (b) Original

Figure 13: Incompressible hull pressure pulse phase angle at the first four harmonic frequencies from the FVM simulation

Finally a proper orthogonal decomposition is utilized to identify the highest energy accumulation on the hull geometry in order to assess possible configurations of the sensor array geometry. The first four mode shapes are given in Figure *14*, where the value range is normalized between -1 and 1 respectively, although the POD mode energies in Figure *15* suggest that only the first 2 modes are relevant for this assessment. More than 90% of the energy lies in the first mode and almost all of the remaining one in the second. Similar to previous studies of POD evaluations of hull pressure, the shapes are independent of the exact propeller design and thus an excellent tool to assess a more generalized shape information about the acoustic impact on the hull. In addition, the underlying data is based on the complete time series simulation data and not restricted to single frequencies. As the HyPNoS prediction algorithm is expected to achieve spectral results across large frequency ranges, the first mode is the most relevant information for the sensor placement. At the higher modes there seems to be a slight shifting of the patterns on the hull, with consistent morphological features.

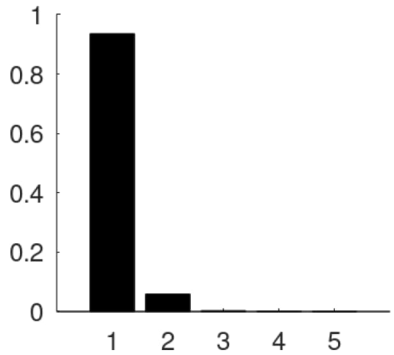




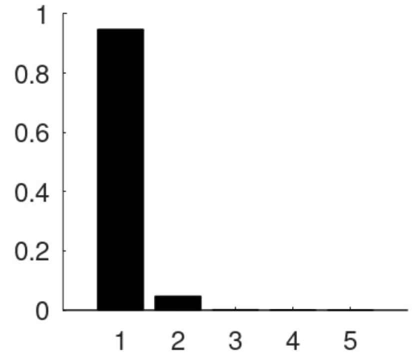
(a) Noise optimized (b) Original

Figure 14: First four POD modes from the pressure data sets in the FVM simulation

Based on this information, it is decided that in the final system only one sensor is required directly above the propeller at the intersection of the vessel centerline and the propeller plane. A secondary sensor is placed at the border of the shown interrogation region in the propeller plane on the portside to be able to implement a collaborative decision-making process in order to enhance certainty of the prediction. An additional aspect is the increased redundancy and reliability as it was found during the field tests, that the centerline position is occasionally submerged in bilge water, which may alter the vibration characteristics of the sensor fundamentally and thus lead to unphysical predictions.



(a) Noise optimized



(b) Original

Figure 15: POD mode energy distribution over the first four mode shapes

Work Process 3

Work process 3 is mainly concerned with the collection and evaluation of data to assess the initial noise levels, the achieved improvement with the optimized design, obtain validation data for the numerical simulations in work process 2 and most importantly acquiring a sufficiently large database for the development of the HyPNoS live prediction algorithm. Large sets of acceleration hull data and acoustic underwater pressure have been obtained and post-processed. After the second measurement the Milestone S1 "Measurement data available" has been achieved in the project, which was the requirement for the development of the algorithm in work process 4. There were a total amount of three measurement campaigns undertaken in the project:

1. Sea-trial measurement with optimized propellers (INSPIRATION) – June 2022
2. In operation measurements transit and berthing with original and optimized propellers (CELEBRATION, INSPIRATION) – September 2022
3. Commissioning and validation of the HyPNoS with optimized propellers (INSPIRATION) – Mar 2024

Before the measurements there was an extensive qualification of SCHOTTEL personnel by the external vessel noise consultant DW-Shipconsult regarding measurement and post-processing of underwater noise data, followed by procuring, activating and commissioning measurement equipment, such as temporary installable vibration sensors, a hydrophone and a calibrator for the hydrophone. After the second measurement campaign another five lectures have been given by DW-Shipconsult regarding post-processing of the generated data, in particular the underwater noise measurements, which have to be translated from pressure data to sound levels and subsequently corrected regarding environment conditions and converted to source levels in order to be applicable for comparison to given limits and the possible user output. Additional information was given on the correlation between vibration and underwater noise, however, as expected, there is very little data on the subject.

The first measurement was scheduled during the sea trials of the INSPIRATION in June 2022, where SCHOTTEL acquired vibration data and BC Ferries collected underwater noise data by passing the Port Vancouver Boundary Pass Hydrophone test track operated by JASCO Applied Sciences. This third party data could serve as validated reference for the SCHOTTEL measurements. In these measurements during the sea trials accelerometer sensor data of the hull has been collected with 12 sensors above the propeller on one side of the double ended ferry at the locations indicated in Figure 16, where the positions on starboard and portside frame 6 have also been measured in x and y direction.

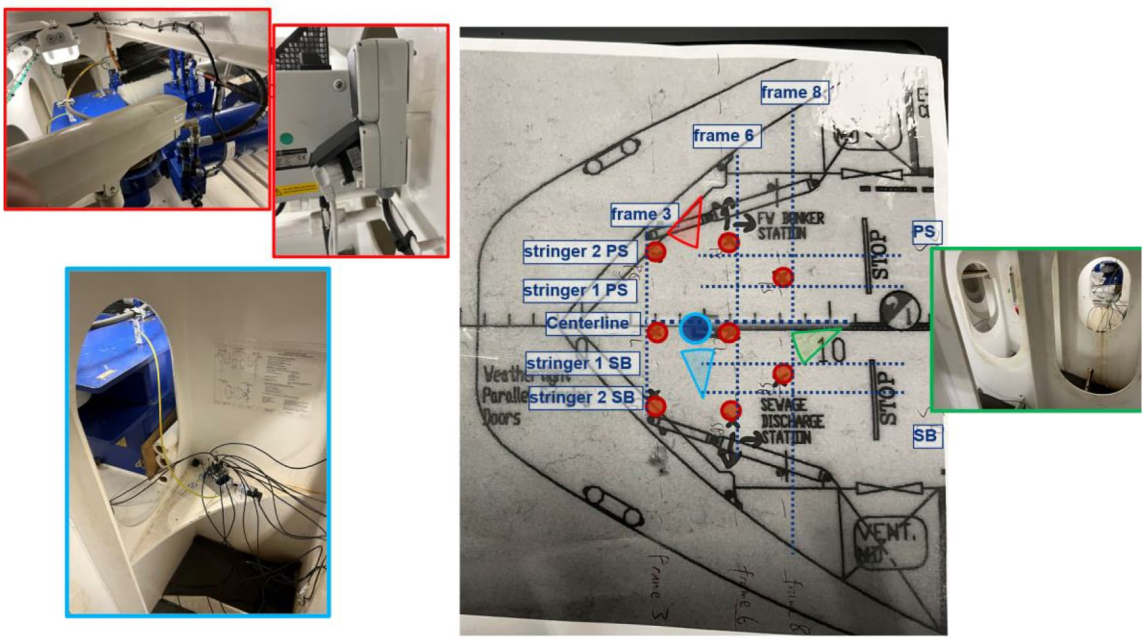
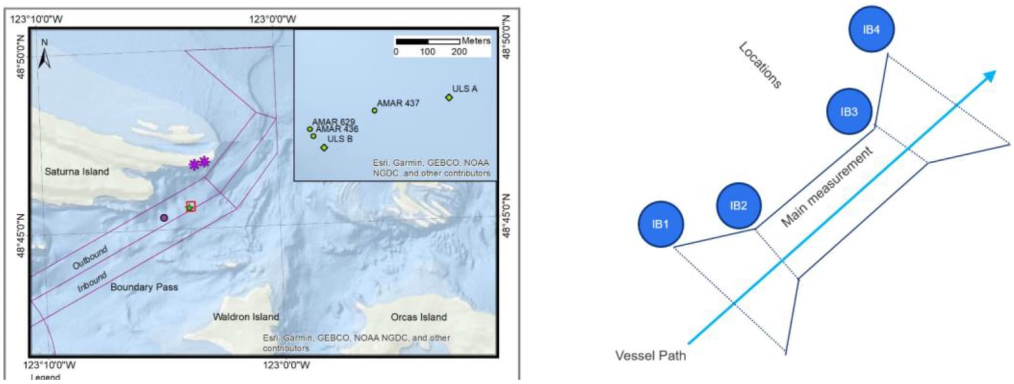


Figure 16: Vibration sensor positions on vessel hull

During the test runs with varying vessel speed across the Boundary Pass designated test track shown in Figure 17 (a) as a map and in (b) as a schematic of the test track with the locations of the hydrophones indicated for the inbound (IB) case. Vibration data has been collected on the aft end of the vessel for each operation point measurement, which consisted of two runs along the Boundary Pass path in inbound and outbound direction. Different operation points or vessel speeds were investigated with three and four generator sets active. Additionally, on the way back to port the setup was changed to the front end of the vessel, which allowed to record slamming noise. During the measurement it was noted that the rudder steering mechanism is a significant noise source, which cannot be turned off, as it is automated. This leads to contaminated data as there is periodic noise overlayed on the measurement. It is believed that this noise can be filtered out in the post-processing. However, the effects on the radiated noise underwater are unknown at this point.

Besides the vibration data on the test track itself the approach to the track is also recorded regarding the acceleration, in order to increase the data fidelity. The underwater noise measurement from the four hydrophones placed along the route was conducted by JASCO in cooperation with BC Ferries. Data generated by JASCO has been shared with SCHOTTEL afterward in the form of final evaluated source level and radiated noise level signature in 1/3 octaves. The raw measured noise data from JASCO could not be obtained by SCHOTTEL. This would have been particularly interesting in order to correlate the acceleration time series with the measured far-field noise and also to be able to utilize the measurements for approach and departure of the Boundary Pass.



(a) (b)

Figure 17: Boundary Pass measurement bathymetry and procedure

The measurements in September 2022 have been successfully planned, executed and finalized where both the INSPIRATION with the optimized propeller design and CELEBRATION with the old propeller design have been analyzed for three consecutive days during transit on 2 days with different vessel speeds and during the berthing condition for 1 day at port. In Figure 18 the measurement locations within the Strait of Georgia are indicated for both vessels. For the measurements in transit a small vessel was chartered in the region, which picked up the measurement engineer for each day of transit measurements. Due to weather conditions some planned test runs had to be cancelled, as it was deemed to dangerous to disembark with the measurement boat.

INSPIRATION	CELEBRATION

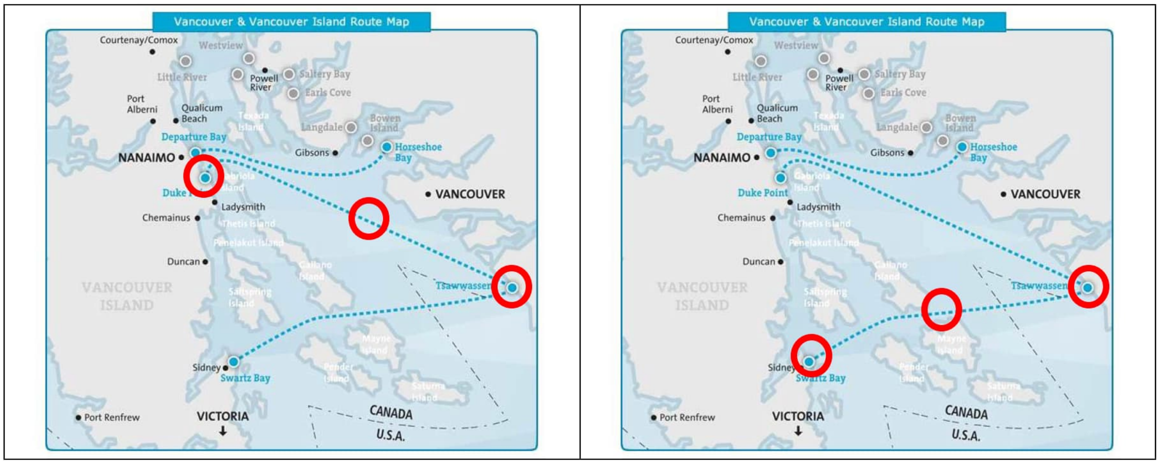
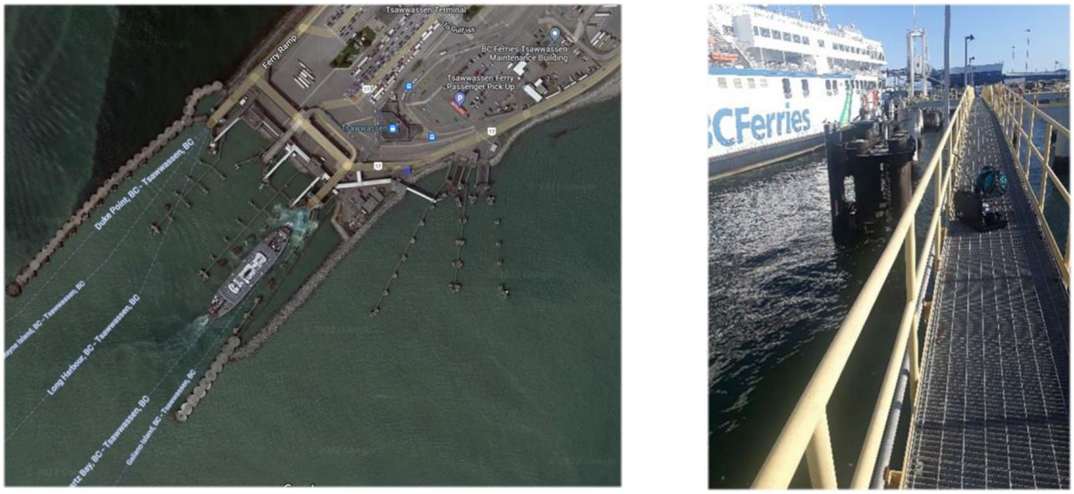


Figure 18: Geographical locations of measurements

For the measurement the equipment was calibrated at the office with a calibrator that was procured as part of this project to adjust the measured acoustic pressure according to a known test noise source, which increased the accuracy and thus quality of the generated data set on site. From the training and the deeper understanding of the challenges associated with measuring and post-processing underwater vessel noise, it was decided to measure only constant operation during transit with different constant vessel speeds around the design point, instead of acceleration and deceleration maneuvers.

Due to the necessity to install the measurement equipment off operation hours of the ferry both sides of the double ended vessel had to be prepared over night and the side for evaluation was changed depending on the direction of travel of the vessel. A wealth of data has been produced with the same vibration sensor locations indicated in Figure 16, however, only z-axis directional measurements were performed due to a lack of sensors as both ends had to be equipped and also because initial screening of the data of the 1. measurement campaign revealed that the acceleration data parallel to the hull surface might be neglected. In this campaign SCHOTTEL produced own high quality underwater noise measurements with SCHOTTEL own equipment including a handheld hydrophone. The hydrophone was based on the chartered measurement boat, which was placed along the natural route of the respective BC Ferries vessel with one engineer on the ferry and one with the hydrophone. The ferry-based engineer was in close communication with BC Ferries to prepare the operation points for data collection and also with the measurement engineer on the measurement boat to coordinate the times for passing.

For the berthing measurements the procedure was adjusted as the hydrophone was handheld from a pier at the local mooring dolphin structure at Tsawwassen port, where one of the engineers exited the ferry during the maneuver. A satellite view of the maneuver is shown in Figure 19 (a) and a photograph of the measurement setup on the dolphin structure is in (b). During the process it was aimed to have the power of the main propeller constant.



(a) (b)

Figure 19: Berthing measurement map and setup

The individual data sets obtained for transit and berthing in the 2. campaign are summarized in Table 2 for the CELEBRATION and in Table 3 for the INSPIRATION, where rejected runs are indicated in red. Ship speeds and powers are averaged over the measurement time.

Table 2: Runs in 2. Campaign, CELEBRATION

Trail no.	from	to	Date	ship speed
1	Swartz Bay	Tsawwassen	16.09.2022	15 kn
2	Tsawwassen	Swartz Bay	16.09.2022	15.1 kn
3	Swartz Bay	Tsawwassen	16.09.2022	16kn
4	Tsawwassen	Swartz Bay	16.09.2022	16kn
5	Swartz Bay	Tsawwassen	16.09.2022	17kn
6	Tsawwassen	Swartz Bay	16.09.2022	17kn
7	Swartz Bay	Tsawwassen	16.09.2022	17.8kn
8	Tsawwassen	Swartz Bay	16.09.2022	17.8kn
9	Swartz Bay	Tsawwassen	17.09.2022	19kn
10	Tsawwassen	Swartz Bay	17.09.2022	19kn
11	Swartz Bay	Tsawwassen	17.09.2022	20kn
12	Tsawwassen	Swartz Bay	17.09.2022	20kn
Berthing				**Power prop 1**
B1	Tsawwassen		18.09.2022	2,8MW

B2	Tsawwassen	18.09.2022	2,7MW
B3	Tsawwassen	18.09.2022	2,6MW
B4	Tsawwassen	18.09.2022	2.6MW

Table 3: Runs in 2. Campaign, INSPIRATION

Trail no.	from	to	Date	ship speed
13	Duke Point	Tsawwassen	21.09.2022	ca 15kn
14	Tsawwassen	Duke Point	21.09.2022	?
15	Duke Point	Tsawwassen	21.09.2022	15kn
16	Tsawwassen	Duke Point	21.09.2022	15.8kn
17	Duke Point	Tsawwassen	21.09.2022	16.9kn
18	Tsawwassen	Duke Point	21.09.2022	17kn
19	Duke Point	Tsawwassen	21.09.2022	17.9kn
20	Tsawwassen	Duke Point	22.09.2022	18.2kn
21	Duke Point	Tsawwassen	22.09.2022	19.2kn
22	Tsawwassen	Duke Point	22.09.2022	21.2kn

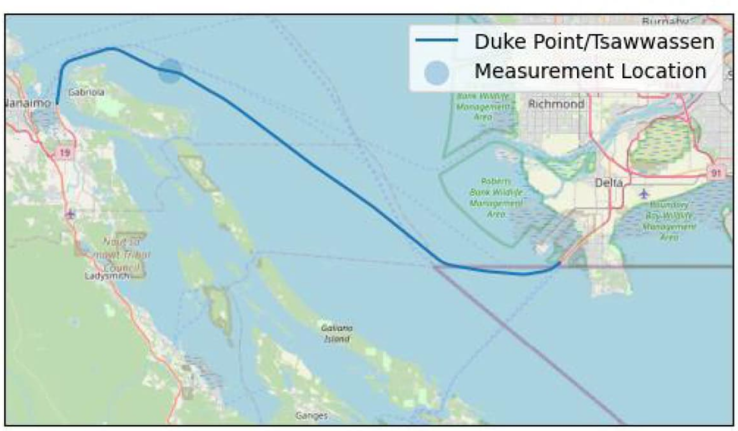
Berthing			Power prop 1
B5	Tsawwassen	23.09.2022	2.7MW
B6	Tsawwassen	23.09.2022	2.6MW
B7	Tsawwassen	23.09.2022	2.4MW

In the third and final measurement campaign the HyPNoS was also installed on the vessel with the two selected vibration sensors and commissioned by two software engineers. The installation of the system on-board the INSPIRATION is shown in Figure 20 (a) and the secondary sensor off the centerline in (b). Unfortunately, the system could not be connected to the internet on this campaign as there was no capacity to adjust the BC Ferries firewall settings before the measurement and a temporary mobile connection for testing purposes could not be established due to the electromagnetic radiation insulation of the vessel steel structure around the ECR. The final measurement campaign consisted of two transit runs at $v_s = 19.5kn$ with the INSPIRATION with optimized propellers in March 2024. In Figure 21 (a) the location between Nanaimo and Vancouver in the Strait of Georgia is shown where the measurement took place. During the measurement two software engineers monitored the health of the HyPNoS and were in communication with the bridge to prepare the measurement run, while one measurement engineer was located with the hydrophone. In (b) and (c) the GPS obtained path of the vessel during the measurement is illustrated with respect to the measurement hydrophone and its distance at CPA. There seems to be a curvature in the path of the second measurement, which could mean that both vibration and URN measurement might be contaminated with rudder noise and the URN averaging requires consideration of the curvature of the path.

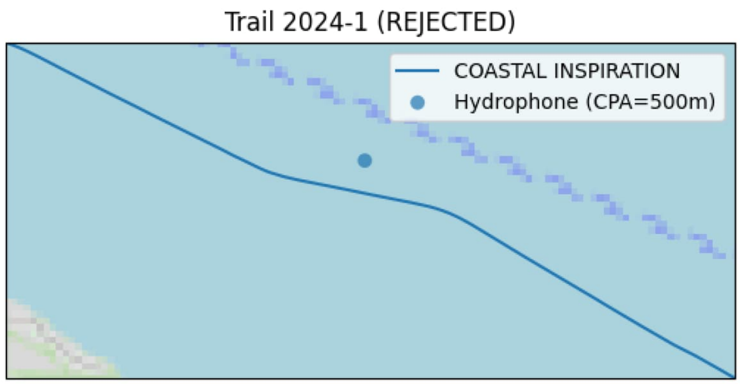
During this measurement the HyPNoS was working without human interference in order to obtain a validation data set. The hydrophone for the reference measurement was hand held from a fishing boat with the engines turned off during the passing procedure. In first measurement the closest point of approach was at $r = 500m$ and noise is contaminating the measurement data, which make it unusable. For the second passing, the closest point of approach was at $r = 150m$ with good data quality besides the curved vessel trajectory. There have been further tests with the system at $v_s = 16kn$, $18kn$ and $20kn$ without URN measurements, that can be used for validation with data collected in measurement campaign 2.

(a) (b)

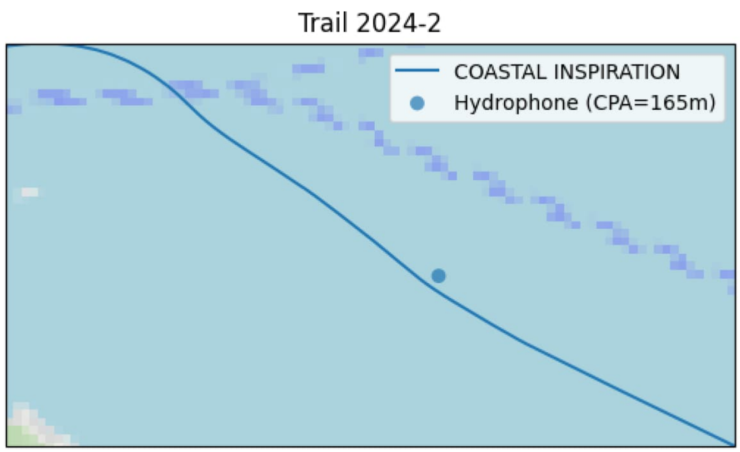
Figure 20: HyPNoS installed in the INSPIRATION



(a) Location of measurement



(b) Vessel trajectory, run 1



(c) Vessel trajectory, run 2

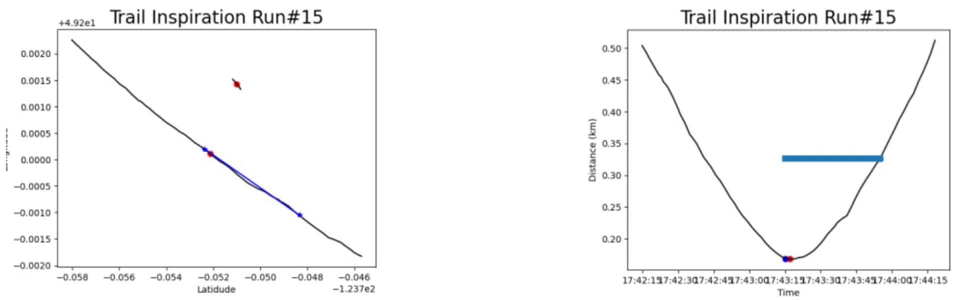
Figure 21: 3. Measurement geographical setup

For the data post processing of the measurement campaigns, the software Flexpro is used for which several scripts were developed to automate the process of generating acoustic radiated noise level signatures from the measured acoustic pressure. This includes a conversion from receiver to source location, with a developed method for environment correction, which respects reflection of the sound path at the free water surface and the ground.

Work Process 4

Regarding work process 4, the sets of data from measurement campaign 1 and 2 were investigated by the software developers to verify the integrity of the data and the completeness. The complete sets were screened and sorted into possible training and test data for the Celebration and the Inspiration. A script was developed to utilize and visualize the GPS tracking data and the possible noise evaluation windows over the time series as exemplified in Figure 22. In (a) the vessel track is shown in black with the closest point of approach to the measurement boat marked in red and the stationary measurement boat also marked in red. In this case the vessel moves from the top left corner to the bottom right, leading to a

DNV averaging window marked in blue. In (b) the same data is plotted as distance curve between sound source and observer.



(a) (b)

Figure 22: Automated evaluation of GPS data and averaging window

An initial literature study has been conducted on the noise data processing methods, which revealed that several competing solution approaches are followed. In the literature study, three works are noted as possible influence on the development on the noise prediction algorithm:

- “Predicting Cavitation-Induced Noise from Marine Propellers”, McIntyre D., 2021, University of Victoria, Master Thesis
- “Ship Underwater Radiated Noise from Onboard Vibrations”, Cintosun E. and Gilroy L. 2021, CRS LOWNOISE report
- “MCDV 2018 Signature Trials On-board Accelerometer Data Analysis”, Dupuis J. and Gilroy L. and Kavanaugh S., DRDC – Atlantic Research Centre report.

The general consensus in these works is, that linear regression analysis might be the most appropriate method for data correlation and that in general a close approximation of the underwater radiated noise with this method is possible. This indicates that there is a close and positive correlation between the measured quantities. However, the notion that reducing speed leads to quieter vessels is not necessarily true, which is clear as the propellers are forced into off-design condition, if they are designed for higher speed. This is particularly true for controllable-pitch propeller vessels with constant speed, as is the case for the BC Ferries vessel under investigation.

Next a market study was undertaken in order to find competing systems already available and identify their main characteristics. There exist some relevant competitors that are actively promoting their solutions as commercial products:

- TSI Ni-CDS (https://tsisl.es/en/technology-and-developments/ni-cds/), which is an onboard system that detects the onset of cavitation and is able to give a warning to the operator,
- SINAY SAS’s Noise Emissions API (https://sinay.ai/en/sinay-hub/noise-api/), which uses the historic vessel data and its main parameters to create a noise estimation

However, it seems that no publicly available commercial product features the same capability that is aimed for with the HyPNoS prototype. There also seem to be

several Transport Canada funded projects that have competing content to the goal of HyPNoS, such as a project by the university of British Columbia in collaboration with Seaspan Shipyards, which also aims to utilize machine learning.
Next the framework on the existing MariHub hardware is designed, which is in its current planning state displayed in Figure 23, with the two possible options of least square regression method (right path) or deep learning (left path). For the deep learning path an offline training neural network hybrid model is selected. To get the engineers accommodated with deep learning technologies, two associated outside experts have been advising SCHOTTEL, from Hamburg Technical University and University of Stuttgart, which have been working with SCHOTTEL in other research projects before.

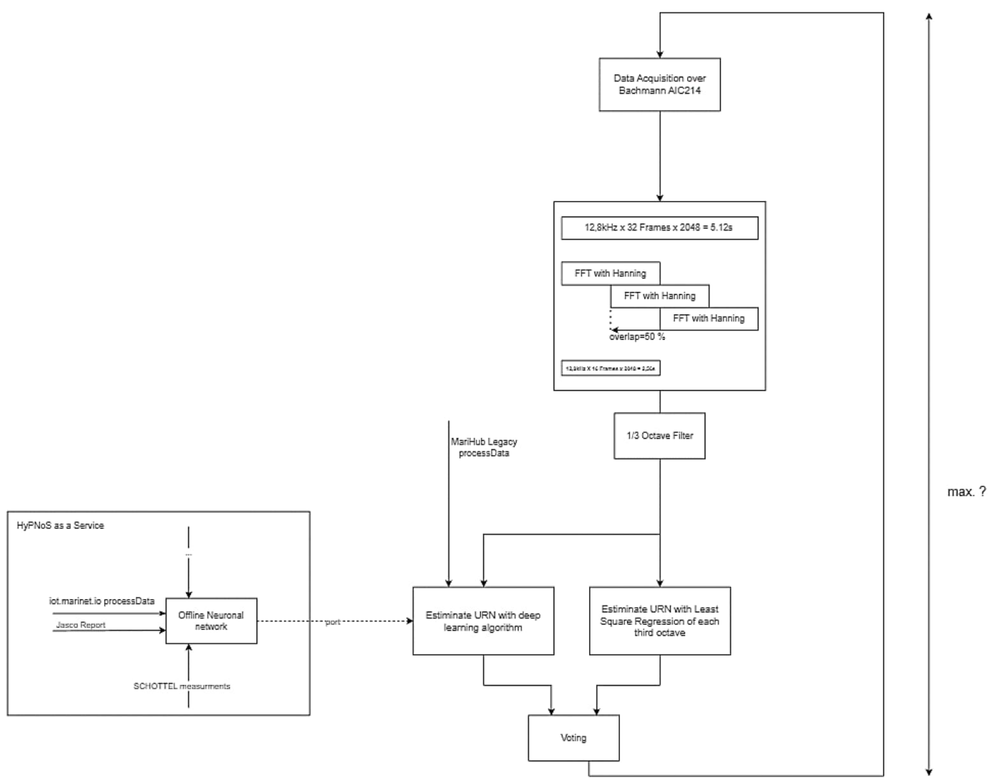


Figure 23: Flow chart of the HyPNoS algorithm on the device

To determine the limitations by the existing MariHub hardware for real time processing of the sensor data is checked in a stress test, where vibration measurement data is processed with a real time FFT. According to the test results, the hardware is capable for the intended purpose. Finally the planned interfaces with BC Ferries for the installation of the base MariHub hardware were clarified and a final technical specification send for approval.

For the development of the algorithm the input-output relationship may be affected by various factors such as:

- **Vessel Characteristics:** The type, size, and design of a vessel can significantly impact its underwater noise emissions. Factors like engine type, propeller design, and hull shape play crucial roles.

- **Operational Parameters:** The vessel's speed, depth, and maneuvering can affect the noise it generates. For example, high speeds or abrupt changes in direction may increase noise levels.

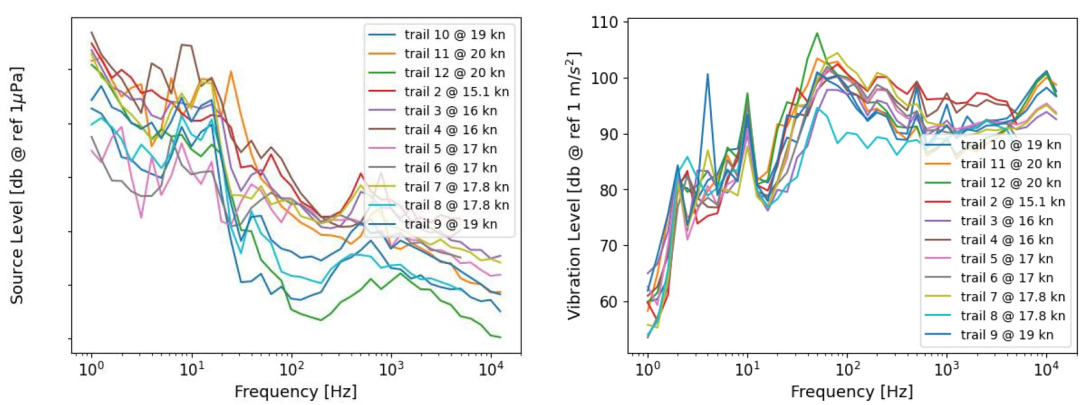
- **Environmental Conditions:** The properties of the water, such as temperature, salinity, and the wind and waves can influence how sound propagates underwater, affecting the observed noise levels.

- **Geographical Features and Bathymetry:** The geography of nearby land formations and the sea floor topology, can impact the reflection and transmission of sound, contributing to the overall noise profile.

Therefore, the development of the monitoring system involves understanding of the acoustic characteristics of different components (e.g., engines, propellers) and how their interactions manifest in the underwater environment. Additionally, it can consider how external factors, like weather conditions or marine traffic density, may influence the noise generated by a vessel. Analyzing and modeling this physical relationship often involves the use of mathematical and computational methods. Machine learning algorithms, for instance, can help identify patterns and correlations within large datasets, allowing for a more nuanced understanding of how certain inputs lead to specific outputs like in this case, the URN of marine vessels. Since the physical relationship is very complex in this case, a data-based approach for estimation of the URN was selected. The various on-board signals that were recorded, are assumed to correlate with the output. Simultaneously, the desired output, namely the URN, was recorded to establish a ground truth for the data-driven analysis. With the nautical position of the vessel and the hydrophone, the ship speed, and the shaft speed the operation points and the corrections for the measurements were reconstructed.

Before processing, all data has been converted with an FFT with Hanning window to 1/3 octave bands, which is automated. For the offline training neural network, the acceleration data obtained by SCHOTTEL and the processed underwater noise data from JASCO and SCHOTTEL is used and ported to the algorithm for the MariHub environment. For the development of the least squares regression approach some tests have been finalized with the source noise which yield high coherence between vibration sensor data and received noise level. However, due to the issues with the conversion to source noise a low coherence between vibration sensor data and source level has been achieved, especially at high frequencies discrepancies due to mathematical transformation of receiver to source appear. Another issue lies in the problematic size of collected data files, which are inconvenient to load and process in the commercial software Flexpro, where an intuitive examination of the data would be possible. As a result, python programming has to be employed for the automated processing.

A correlation of the measurement data between the vibration of the ship's hull and the underwater radiated noise is investigated next. The Figure 24 shows the acquired data at the hydrophone as spectral source level in (a) and from the vibration sensors in (b), which were collected during the trial runs in campaign 2. It is clear from the results and important to understand that the fastest speed does not produce the largest noise, instead it is the speed that creates the most unfavorable off-design condition for the propeller blades of the controllable pitch propeller which leads to the highest noise emission. By observation of both graphs some correlation can be identified, regarding the amplitude order of the different runs.



(a) Hydodynamic (b) Structure

Figure 24: Source level spectra of trial runs for various vessel speeds

The preprocessed data was split randomly into a test and training set. In total there are 8 complete usable runs during transit for the INSPIRATION, with 6 selected as training data and 2 as test data. For the CELEBRATION there are 12 available sets of data with 3 selected for testing. The aim was to have 80% of the data for building up the algorithm, while the other 20% of the data was used to validate the algorithm. For the data-driven approach, the sustainability, flexibility, and maintainability of the algorithm play an important role and must be considered in the conceptual design of the algorithm. Thus, the vision of the algorithm was to develop a fully parameterizable software algorithm that depends mainly on the input signals, the rules, and the outputs. The rules can follow different machine learning approaches, such as neural networks, decision trees, or regression models, and can be applied to the generic algorithm via a configuration file. The rules can be defined as a custom rule set, such as a linear regression (with slope and intercept), or use generated inference from a specific machine learning framework, such as *TensorFlow Lite*. In either case, the software can interpret these rules to make predictions based on the input data. This allows to tune the data model or even to change the machine learning technology to improve the algorithm's performance from time to time. For the validation, the algorithm was switched to the *Least Squares Regression* approach, which in this case relies on the theoretical relationship between acoustic pressure and the particle velocity of the water at the outer hull, which is equivalent to the vibration of the hull.

To deliver a highly adaptable and scalable implementation, as mentioned above, a singleton patterned class, the *GenericAlgorithm,* was developed in C++. This singleton can consume all signals from the I/O middleware and generate output signals depending on a specific ruleset. The Figure 25 shows the concept of the generic algorithm implementation. The output, in this case, the URN can be obtained by various Machine Learning approaches, like a regression mode. After the initialization of the *GenericAlgorithm*, the algorithm predicts the URN based on the given rules in each cycle. The URN displays continuously on local indicators and is also be transmitted to the *SCHOTTEL* IoT cloud platform. The local indicators are not accessible in the SGR during vessel operation.

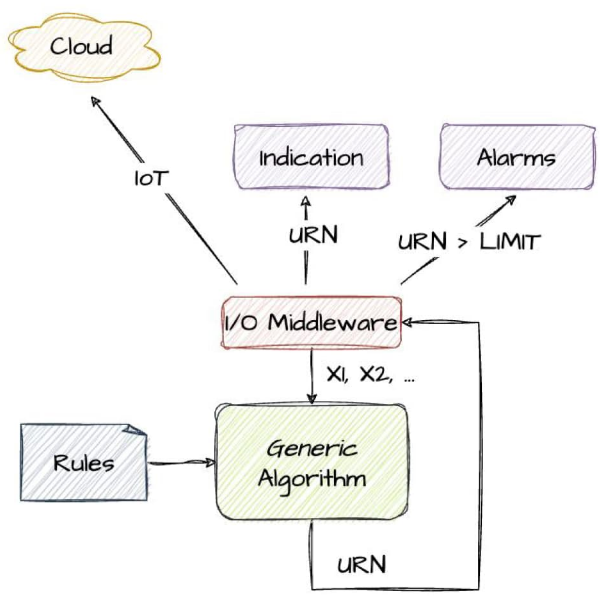


Figure 25: Implementation of *GenericAlgorithm* with the interactions between I/O Middle-ware, Cloud, and local vessel instruments

Within the *Least Squares Regression* approach, a linear regression model over the vibration data (see Figure 24), was used to predict the URN of the vessels. Therefore, a user-defined ruleset is applied. This ruleset was defined as a *LeastSquaresRegressionV1* object and can be interpreted by the software to transform the input signals, as shown in Figure 25. The configuration file is a JSON-formatted text file and can be updated via the parameter management of *MariHub*, in case of model adjustments. In this case, the ruleset follows the procedure from Figure 26.

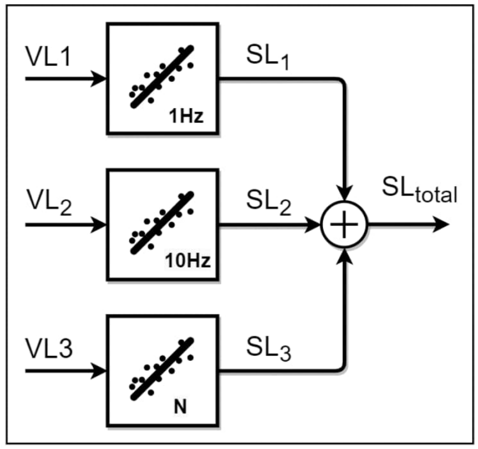


Figure 26: Proceeding *LeastSquaresRegressionV1* to obtain the URN (SL) from on board vibration data (VL)

Each vibration level in the frequency band was transformed with a linear regression model $y = mx + b$ to relate it to the URN levels. This process involved fitting a linear regression line to the vibration data, where “y” represents the transformed URN level, “x” represents the vibration level, “m” is the slope of the regression line, and “b” is the intercept. The JSON-formatted ruleset stores the regression parameters slope and intercept for each of the entire frequency band. After regression to the corresponding URN levels, the URN levels were then summed over the entire frequency band to obtain a comprehensive URN level that can be used for further monitoring.

The algorithm was tested with a software-in-the-loop (SIL) test, where the vibration measurement data of the trial run was used to test the algorithm based on the real vibration profiles of the vessels. Therefore, a test API was also implemented, which would bypass the real measurement over the hardware and apply the sampled data directly to the software algorithm. The accuracy of the URN estimation depends mainly on the quality and number of training data. Currently, the algorithm can operate in real time with an overall mean error of approximately 4 decibels. Comparing the estimated URN with other comparable studies, the outcomes in terms of error are nearly the same. In comparison to this, the mean error in the simulation environment is comparatively higher. The Figure 26 below illustrates the difference between the measured and estimated URN as overall sound pressure level. With this functionality test the milestone S2 “Noise monitoring achieved” was reached in the project.

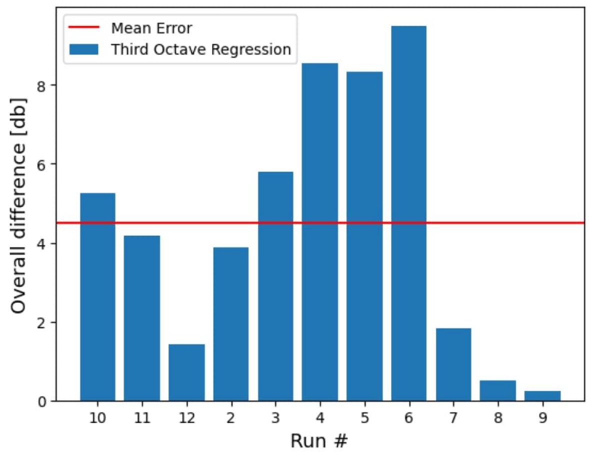


Figure 27: Overall difference between the measured and estimated URN of all trial runs

The high uncertainty regarding the repeatability of underwater noise measurements, due to the disturbances depending on the environment, causes a dynamic error that is currently not considered by the algorithm. This leads to some fluctuations in the spectral prediction quality for example in Figure 28, where the best and worst prediction with the area in between marked in green is compared to a test data set. The experimental signal lies reassuringly within the bounds of the prediction for the frequency range above $f = 100Hz$, while the prediction is $5 - 10dB$ to low at the frequencies $f < 100Hz$. However, the error between upper and lower bound depend highly on frequency for this case with a minimum of $\Delta SPL = 5dB$, which is well in the acceptable range and a maximum of $\Delta SPL = 40dB$, which generally can be considered too large. Therefore, further improvements with more training data are recommended to improve the prediction of URN from time to time. In this case, the algorithm input will also be sent to the cloud. The ground truth, i.e. the URN, has to be obtained from measuring institutions or through further underwater acoustic measurements by *SCHOTTEL*. Adding new training sets to the data-driven analysis, should improve the URN estimation from time to time. This is not restricted to the HyPNoS project vessel, but instead may be continued with other cases benefitting also the Coastal Class with updated algorithms.

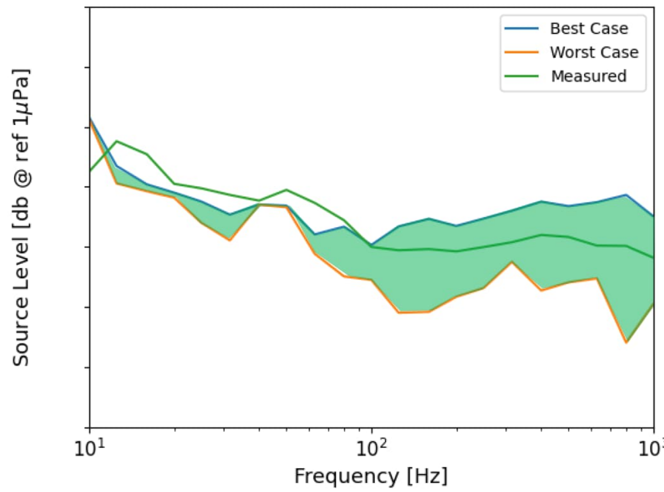


Figure 28: Error band of live prediction algorithm for one example measurement

In the final step the developed software is deployed to the MariHub on the INSPIRATION and the algorithm is validated with the reference measurement from the third measurement campaign. In Figure *29* the final predicted curve at $v_s = 19.5kn$ is given with the corresponding measurements at the same operation point by SCHOTTEL in 2022 and 2024 and by JASCO. While the repeatability of the SCHOTTEL measurement data is sufficiently high, it seems that in the JASCO measurements a region around a frequency of $f = 800Hz$ is producing higher source levels.

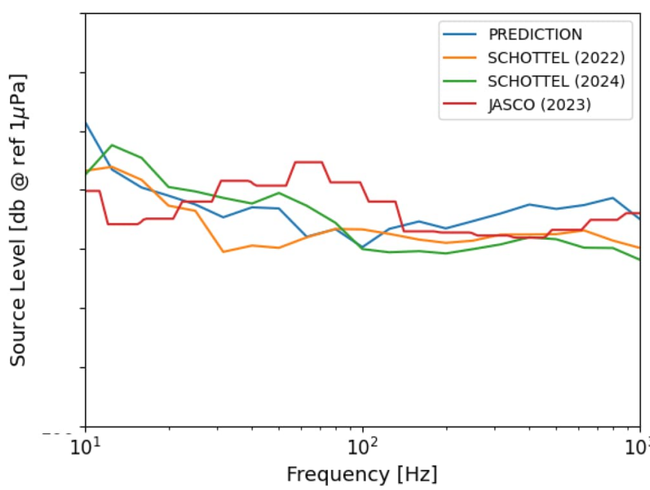


Figure 29: Final system prediction result in comparison to the URN measurements by JASCO and SCHOTTEL at $v_s = 19.5kn$

The live prediction capability of the system is shown in the time series of overall sound pressure level, with dynamic stepwise adjustment of vessel speed in Figure

30. The vessel speed is increased stepwise from $v_s = 16kn$ to $18kn$ to $20kn$, while the system is actively predicting the URN. In the overall SPL the change in noise emissions distinct when the velocities change. The change at the end of the 16kn period can most likely be attributed to a delayed reporting of vessel speed rather than an underprediction of the system. This graph again confirms that higher vessel speeds do not necessarily reduce noise emission for constant speed controllable pitch propellers. This validation process proves the accuracy and reliability of the algorithm under real conditions, which concludes the work process 4.

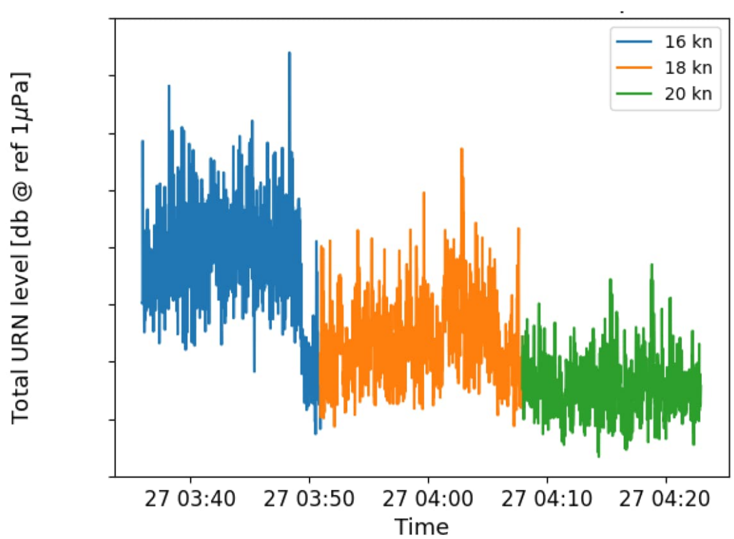
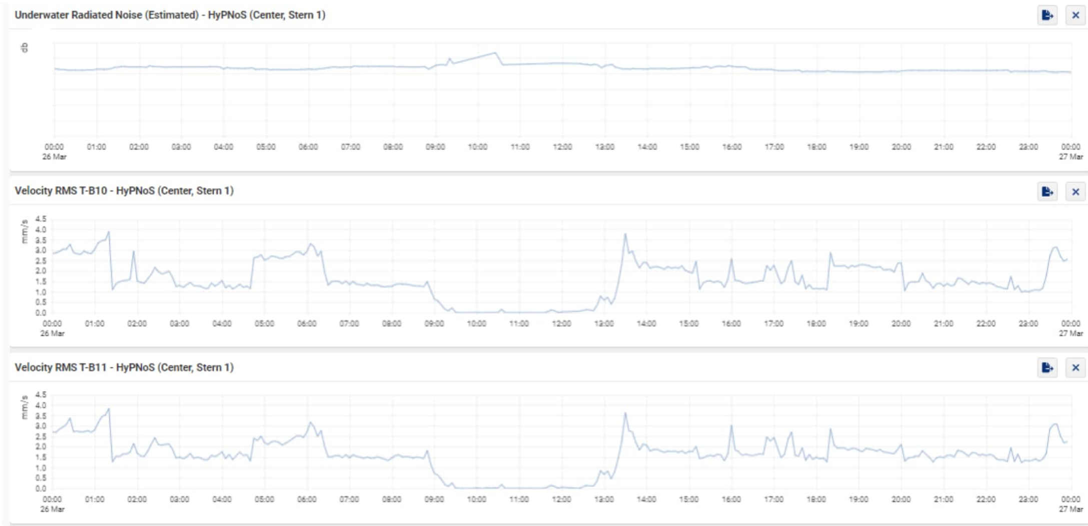
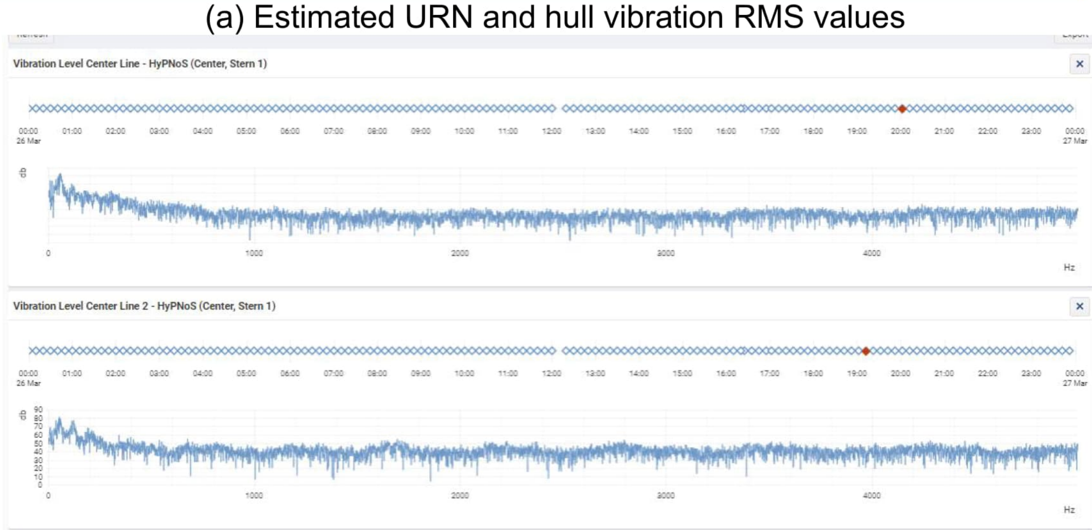


Figure 30: Live prediction with dynamic adjustment of operation point

The predicted URN level as well as the spectrum and RMS values of the vibration sensors are transmitted to the SCHOTTEL IoT cloud platform by the installed MariHub in a secure manner and can be used by the crew operators to monitor the current noise level and by SCHOTTEL for further ML optimisations in the data model. The historical data from the trail run can be seen in Figure 31. BC Ferries is currently working on a permanent internet connection for the monitoring system to send the data permanently to the cloud. SCHOTTEL's data scientists will be able to improve the algorithm from time to time via remote access. An installed remote access framework will eliminate the need for physical access to the onboard equipments, making it possible to do optimisations on the ML model from time to time as an “over-the-air update”. In case of further funded development of the noise monitoring system, other vessel equipment (e.g. rudder, propulsion, engine, GPS) may also be recorded and added to the ML model, to reduce the disturbances in the URN prediction.



(a) Estimated URN and hull vibration RMS values



(b) Vibration spectrum

Figure 31: SCHOTTEL IoT Cloud platform for vessel operators and data scientists

Timeline

Due to scheduling issues regarding the quarter life upgrades of the Coastal Class the main SCHOTTEL measurement campaign with original and optimized propeller for data collection had to be moved to September 2022, a vibration measurement could be taken at the sea trials of the vessel INSPIRATION with the optimized propeller design in June 2022 on short notice.

In the year between the submission of the proposal in May 2021 and the acceptance in May 2022, BC Ferries adjusted their plans for the quarter life upgrade of the three reference vessels to omit variable frequency drives (VFD) or electric motors with adjustable rotation rate for the propeller shaft. As a result, the project plan, which required all possible vessel combinations of original and noise optimized propellers with and without VFD, had to be modified. Instead of measuring the hull vibrations and the underwater noise of all possible combinations and determine the influence of propeller and rotation rate, only the original and noise optimized propellers are analyzed. Thus, the schedule was adjusted to have three measurement campaigns, in particular in June 2022 and in September 2022 to collect data for the development of the noise prediction algorithm and in March 2024 to validate and tune, if necessary, the noise prediction algorithm on site as illustrated in Figure *32*.

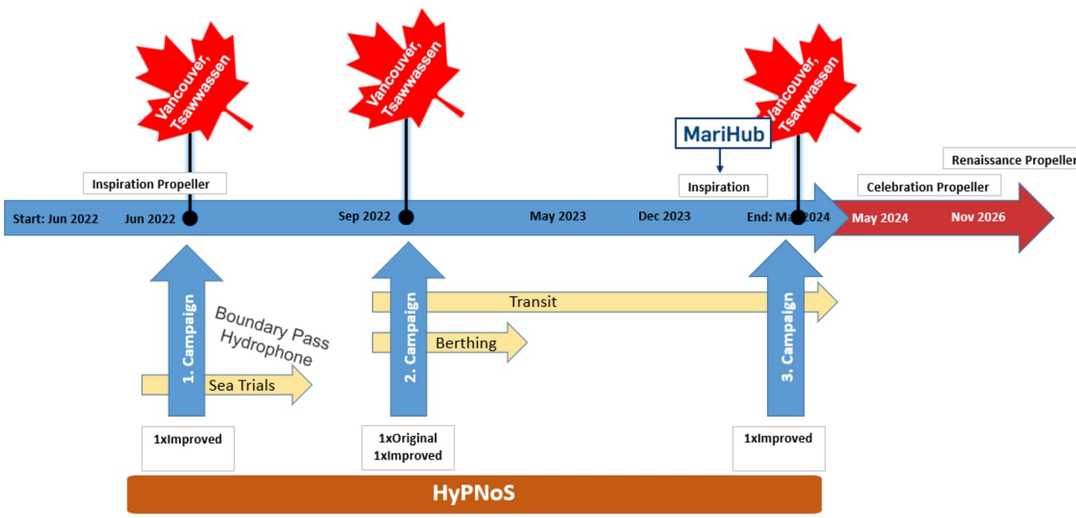


Figure 32: Illustration of final project schedule

3 Performance Indicators

3.1 Objective(s)

The main objective of the project is to reduce the impact of the local vessels in British Columbia and specifically of the BC Ferries operated Coastal Class navigating in the Strait of Georgia and therefore reducing the impact of anthropogenic noise sources on the resident marine biology. To achieve this, numerical methods to predict URN have been extended, propulsion devices with reduced noise signature were tested, the main contributors to the reduction of the vessels noise emission were identified and methods to evaluate real time impact are derived with the installed live monitoring system. The findings were and will be made publicly available via different means of outreach organized by SCHOTTEL and Transport Canada.

The promotion and verification of the effectiveness of retrofits is possible with the collected underwater noise data from the original and noise optimized propeller. The generation of noise awareness among vessel operators is possible by disseminating the results and providing the real time noise monitoring system as a product, once it leaves the prototype stage. The noise prediction methods for the design phase (CFD) have improved in quality and regarding the obtainable data.

The original goals were formulated according to SMART criteria and are repeated again here with green color indicating a fulfilled goal and red a goal that has been failed:

1. By Q4 2023, a numerical URN simulation method based on the finite volume method with resolved turbulence and cavitation coupled with an acoustic analogy has a 20% improved accuracy to the current implementation in the narrowband spectrum in the frequency range between 100Hz and 20kHz. It is able to produce signatures with an error of less than 10dB for shallow water off-design operations of double ended ferries, which is validated for the BC Ferries Coastal class ferries in berthing operation, to improve accuracy of URN prediction for future designs.
2. By Q3 2022 improved propeller and VFD designs, including the on-site combinatory matching is validated by spectral comparison of full-scale measurements obtained in operation near the port of Vancouver. By Q1 2024, the single contributions of the two noise reduction measures obtained in full-scale measurements near the port of Vancouver are compared with the original and improved design in spectral representation, to confirm the improved system design and deduct guidelines and best practices for future vessel and propulsion system designs including a priority of the noise reduction measures in the form of a short document.
3. At the end of Q1 2024, a vessel-specific (BC Ferries Coastal Class) onboard, real-time underwater noise monitoring software is implemented and functional in the current monitoring solution MariNet based on real time vibration measurements at the propulsion unit, with the developed correlations, which are obtained from full-scale measurement data for URN and Vibration. This will facilitate a general reduction of anthropogenic noise in the region of operation for the Coastal class ferries, as the feedback can be included in BC Ferries operating directives.
4. At the end of the project run time, the outcomes of the measurements and simulations in the form of spectral evaluation in a frequency range from 100Hz to 20kHz, as well as the success and accuracy of correlating on-board vibration signals with URN is published in the form of a conference talk or a webinar, or other means available, with a written summary manuscript. Thereby, the visibility of the approach

is increased for industry, indigenous groups and other marine stakeholders and the assessment of the effectiveness of such measures is transferred to the associated public discussion, in order to make the approach accepted and open the way for adaption of the methods for other Canadian shipping lanes and vessel owners. In the case that no correlation between the signals is detected, the findings will be published with an extensive discussion of the possible underlying reasons of insufficient signal matching.

As seen by the indicated colors, the goals have been fulfilled or mostly fulfilled by the project. One main difference is the change in the quarter life upgrade scope and schedule, which means the VFDs were not installed during the project time. Therefore, the vessel was again a constant speed shaftline vessel without combinatory mode, which of course made the goal 2 impossible to achieve. Regarding goal 1, it turned out that the workload of the measurements was underpredicted and thus the resources from work process 2 were reallocated to work process 3. This in turn meant that only the transit condition was simulated.

3.2 Work process #1: Project management

The goals in work process 1 were mostly fulfilled.

- **Coordinate regular meetings with BC Ferries (to discuss measurement campaigns, simulations regarding input and results, etc.)**
  There has been extensive communication with the project partner BC Ferries, during the planning of the measurement campaigns. Afterwards the acquired data during measurement campaign 1 has been exchanged. For the implementation of the HyPNoS prototype there has been communication regarding interfaces and delivery coordination during the quarter life upgrade.

  Fulfilled

- **Develop periodical reporting on the Project progress**
  This report comprises the final project report an the progress report in Spring 2023 showed the state of the project in period of the fiscal year 2021-2022.

  Fulfilled

- **Develop and edit manuscript on Project results**
  The manuscript for publication is currently being worked on. The other paper released with results from HyPNoS is not exclusively focused on HyPNoS and thus does not count fully towards this performance indicator.

Continued

- **Develop presentation material**
There has been a wealth of presentation material over the complete project for three different conferences and web platforms. More will follow with the final publications.

Fulfilled

- **Present Project results at an event**
For public presentation of the first results the Canadian Ferry Association (CFA) conference and trade show 2023 in September located in Vancouver, British Columbia was selected, where SCHOTTEL held a presentation. Furthermore, the findings of the project were included in a presentation at STG-Hauptversammlung, a national shipbuilding conference in Germany, which is accompanied by a journal paper.

Fulfilled

3.3 Work process #2: Development of underwater radiated noise prediction tools

The goals in work process 2 were mostly fulfilled.

- **Select operation point for validation**
An operation point at 19kn was selected, which is equivalent to measurement 9 of CELEBRATION. The selected point is given in Table 4.

Table 4: Selected operation point for validation

Trail no.	9
from	Swartz Bay
to	Tsawwassen
Date	17.09.2022
time	08:52
side	PS
Pitch 1	24.5°
Pitch 2	FF

depth	360m
Power E-Motor	8 to 7 MW
ship speed	19kn
seastate	1
notes	no traffic
Waves	calm

Fulfilled

- **Adapt the computational fluid dynamics setups to double ended ferries**
  An adjusted setup has been created

Fulfilled

- **Run a literature study regarding reflection for acoustic propagation**
  A literature study revealed some interesting approaches such as Göttsche "Evaluation of Underwater Sound Propagation of a Catamaran with Cavitating Propellers" that lead to the conclusion that the reflections need to be considered in the acoustic method. However, the number of literature sources found that actively investigates these effects from CFD simulations is quite low.

Fulfilled

- **Implement a method to respect reflections**
  Reflections at the free water surface are considered in the setup, by implementing a static free water surface from a resistance simulation. The sea floor is respected by considering the respective domain height. However, it is unlikely that this affects the acoustic method, due to numerical dissipation. In future investigations reflections have to be considered in the acoustic methods and a proper comparison is required.

Fulfilled

- **Run simulations of the case**
  A two-phase LES simulation has been conducted for the original and the noise optimized propeller design as shown in Figure *10*.

Fulfilled

- **Run acoustic post-processing of the time series simulations**
  The acoustic emission over 5 rotations have been post-processed.

  Fulfilled

- **Validate the spectral acoustic emission at the observer points**
  A comparison has been made in Figure *2* with similar results.

  Fulfilled

- **Quantify the improvements by considering shallow water effects**
  Shallow water operation points have not been considered due to a lack of resources.

  Not Fulfilled

3.4 Work process #3: Tests and trials

The goals in work process 3 were fulfilled.

- **Train measurement engineers**
  The training of the measurement engineers was completed successfully. In the 2. and 3. measurement campaign the acquired knowledge had to be applied in real application on site. Additional measurement material, particularly the calibrator for the measurement equipment, was required after the training, which increased the quality of the data. Without the training this aspect would have been neglected.

  Fulfilled

- **Clarify the interfaces**
  The interfaces and locations for the measurement have been successfully coordinated with BC Ferries, so that vibration measurements could take place during regular ferry operation. For the final permanently installed system, the number of interfaces has been reduced in discussion with BC Ferries to accommodate the new upgrade schedule. (see Figure *6*)

  Fulfilled

- **Prepare the on-site installation**
  Before and during the 1. measurement campaign on the Inspiration, the locations of the sensors were determined according to supposed effect of the propeller onto the hull excitation and accessibility on site. The on-site installation was prepared successfully in office beforehand and on site for both

ends of the vessels INSPIRATION and CELEBRATION during the 2. Campaign and for the INSPIRATION during the 3. Campaign.

Fulfilled

- **Collect measurement data of all target case vessels with original and improved systems for cruising, acceleration, and deceleration operation**
  In the 1. campaign hull vibration data has been collected for 4 different operation points with 4 passes each for the Inspiration at different speeds and with different number of active generators during constant vessel speed transit. In addition, processed acoustic signature data has been sent by JASCO for the same operation points. In the 2. campaign SCHOTTEL collected data for both hull vibration and underwater noise. During transit the INSPIRATION (optimized propeller) was measured with 15 to $21kn$ in $1kn$ steps with a total of 10 runs and the CELEBRATION (original propeller) for 6 different speeds from 15 to $20kn$ in $1kn$ steps with a total of 12 runs. During the measurement preparation and while acquiring more know-how during the training it was decided that acceleration and deceleration data is not required and difficult to obtain and utilize in a meaningful way.

  Partly Fulfilled

- **Collect measurement data of all target case vessels with original and improved systems for berthing operation**
  For berthing, 3 sets of data have been recorded with the INSPIRATION and 4 for the CELEBRATION with slightly varying average power consumption of the propeller. However, these data sets have not been evaluated for the simulation in work process 2.

  Fulfilled

- **Create usable underwater noise emission data for human interpretation and quantify the effects of the noise reduction measures applied to the target case vessels**
  For the 1. measurement campaign this was provided by JASCO, for the 2. measurement campaign hydrophone evaluation algorithms were developed at SCHOTTEL to automate the process. The procedure is validated with the measurement data and applied to the data sets from the 2. and 3. measurement campaign.

  Fulfilled

- **Validate noise measurement system with improved system**

This indicator has been achieved with measurement data from the 3. measurement campaign in Figure *29*.

Fulfilled

- **Verification of data**
  The measurement data for the 2. Measurement campaign is fully verified. Some measurements had to be rejected. Regarding the underwater noise measurements for the Celebration 3 out of 12 measurements are rejected and for the Inspiration 2 out of 10. For the 1. measurement campaign the data was verified by JASCO, which rejected 7 out of 19 measurements. The vibration measurements are verified and are all usable, however, intermittent noise caused by the rudder steering mechanism as well as slamming during sea trials due to light loading need to be considered in the data sets. For the 3. campaign one URN measurement data set was rejected as the distance was too far and there was signal noise and the other one accepted.

  Fulfilled

- **Transform to noise source level**
  An automated way of transformation between post-processed data from receiver to source was developed in the software solution FlexPro.

  Fulfilled

3.5 Work process #4: Noise monitoring system

The goals in work process 4 were mostly fulfilled.

- **Develop a data processing method**
  An automated post-processing of the onboard vibration and far-field noise data has been developed with frequency domain conversion with appropriate window functions and synthesizing into 1/3 octave bands. A correction for the conversion from radiated noise level to monopole source level is implemented that considers the free water surface and the water depth.

  Fulfilled

- **Cross correlate with appropriate measure**
  Least squares regression has been identified as the typically used and most appropriate data correlation method for now. Deep learning methods have been investigated in detail, but seemed not appropriate in a ready to use state, as the learning data was insufficient. In the future, exploring a sparse data input neural network might be helpful.

Fulfilled

- **Develop a data mapping model**
  The obtained data has been categorized in training and test sets. Both sets have been processed with developed scripts. The training data is used to achieve the correlation function, leading to good agreement with the test sets.

Fulfilled

- **Develop a real-time monitoring system**
  A real time monitoring system has been successfully developed with good results.

Fulfilled

- **Develop surrogate models for measured parameters**
  As the final correlation model was a simple linear regression, the hardware was able to run it live without the need for surrogate models. This might be an issue arising later, if machine learning is utilized to its full potential in the monitoring system.

Not required

- **Implement the real-time monitoring system in existing software**
  A hardware test has been performed successfully, final hardware requirements have been specified and a high level design of the implementation was prepared. The hardware was ordered from the supplier and modified accordingly for the purpose with a Windows computer to connect to the vessel internet. The algorithms were translated to machine code and uploaded to the MariHub controller.

Fulfilled

3.6 Project Outcomes

HyPNoS is actively contributing to identify, test and develop quiet vessel technologies and designs. The collected performance data over the first fiscal year 2021-2022 sorted by indicators that are applicable to the Project are listed here.

- **# of participants that attended courses or workshops**
  ≈350 (at 3 conferences)

- **# of individuals that received training or information**

≈21
  - 5 received training within SCHOTTEL
  - ≈16 received information about the campaign at BC Ferries

- **# of technologies developed (such as data processing methods, mapping models, real-time monitoring systems, etc.)**
  5
  - Evaluation scripts for GPS tracking data
  - Flexpro data processing scripts
  - Python data evaluation scripts for verification methods between commercial software and SCHOTTEL approach
  - Generic live algorithm based on PLC
  - On-board live URN monitoring system

- **# of technologies evaluated**
  4
  - Transformation of acoustic pressure time series information into sound levels
  - Linear regression analysis of hull data with far-field underwater acoustics
  - Evaluation of hull pressure information from numerical simulation boundaries
  - AI technology running on standard condition monitoring system (technical readiness)

4 Project Issues and Risk Factors

In the following Table 5 the detected risks from the original submission, categorized by scientific-technological risks and economic risks, and their corresponding probabilities and impact are listed. Here the estimate of probability and impact ranges from value 1 (low) to value 3 (high). For the total rating of a risk the probability and impact are multiplied, so the scale ranges from value 1 (low) to value 9 (high). In addition, the response to each risk is given, as well as the action in the case of an accepted risk. In the column “Occurred” it is indicated if the risk occurred during the project (1), or if the risk did not occur (0). If it is unknown if the risk occurred or may occur after the project runtime it is shown with (?).

Table 5: Updated risk register

Nr.	Cat.	Description	Probability	Impact	Rating	Response	Measure	Occured
1	sci.-techn.	Risk, that the calculation time of the CFD simulation to reach acoustically converged solution states is too long to be industrially feasible	1.7	1.2	2.0	Mitigate	Develop a method to use steady state calculations to initialize the unsteady solver interPhaseChangeDyMFoam	0
2	sci.-techn.	Risk, that the numerical and experimental results can not reach agreement and the underlying causes can not be identified in the availble time	1.2	1.5	1.8	Accept	Deviations have to be accepted, suspected causes require documentation for publication and future investigations	0
4	sci.-techn.	Risk, that disturbance sources during the experimental URN measurements are not detected and render the results unusable	1.3	2.7	3.5	Mitigate	Minimum of two separate measurement runs per condition with a total of nine measurement conditions on separate measurement days	0
5	sci.-techn.	Risk, that disturbance sources during the vibration measurements are not detected and influence the results	1.2	2.7	3.2	Mitigate	Several sensors at different locations at unit and in vessel with a total of nine measurement conditions on separate measurement days, Check of vibration sensors on preparation day	0
6	sci.-techn.	Risk, that the URN in berthing mode can not be evaluated in a usable way	2.6	2.7	7.0	Transfer	Invest in third-party measurement of DW-shipconsult for future berthing mode measurements and repeat failed measurements on own cost	1
7	sci.-techn.	Risk, that the URN level cannot be determined with sufficient accuracy for unknown reasons with the simulation approach	2.0	1.3	2.6	Accept	These findings are an important result of the project and determine the direction of future projects	0
8	sci.-techn.	Risk, that the measurement time of vibra-	1.5	1.9	2.9	Avoid	Receive external training from URN specialist DW-	0

		tion and URN measurements cannot be aligned					shipconsult before measurement campaign, Three hammer impacts required for calibration of measurement start time	
9	sci.-techn.	Risk, that the GPS location signal of source and observer ship cannot be obtained due to bridge interface problems	2.1	1.7	3.6	Mitigate	Utilize two independent GPS measurements per vessel with onboard systems and SCHOTTEL USB-GPS receiver	0
10	sci.-techn.	Risk, that the GPS position accuracy is not sufficient for the correction factors of URN	1.1	1.4	1.5	Accept	Conduct error analysis to estimate the accuracy of the URN measurement	0
11	sci.-techn.	Risk, that the sonar can not be turned off on the pilot boat	1.4	3.0	4.2	Avoid	Charter boat that has sonar that can be turned off	0
12	sci.-techn.	Risk, that the water depth needs to be measured at the same time as the URN measurement, due to drift or similar issues	1.1	3.0	3.3	Accept	Exact measurement procedure has to be developed in training with third-party expert DW-shipconsult	0
13	sci.-techn.	Risk, that the interface clarification on site (third party sonar, rudder, etc.) might take longer than planned and extends the measurement preparation time extensively	1.8	2.5	4.5	Mitigate	Communication of interfaces beforehand, Request interface descriptions from partner BC Ferries beforehand	0
14	sci.-techn.	Risk, that unknown parameters prevent a useful correlation between vibration and URN during evaluation phase	1.1	2.9	3.2	Accept	Use data sets from different runs to treat disturbances as signal noise	0
15	sci.-techn.	Risk, that the algorithm is not fit to deal with different external parameters (such as tank fill levels) after installation of the noise monitioring system	1.3	1.7	2.2	Accept	Continuous support of the system by developers during lifetime of the vessel to adapt code via updates, Follow up investigations after project runtime to identify sources of inaccuracy	?
16	sci.-techn.	Risk, that the correction factors for the URN measurements are applied incorrectly	1.9	2.2	4.2	Avoid	Engineers receive training by third-party expert before measurement campaigns	1
17	sci.-techn.	Risk, that the weather changes between two	1.2	2.6	3.1	Accept	Disregard runs when estimating the reproducibility	0

		opposite runs are severe and the runs can not be compared					of the measurements	
18	sci.-techn.	Risk, that the environment conditions are too extreme for usable measurements	1.1	2.8	3.1	Avoid	Reschedule measurement campaign on SCHOTTEL cost, Flight tickets and hotel reservations have to be flexible	1
19	sci.-techn.	Risk, that interfaces are incorrectly calibrated, or scaling of third-party input data is unknown	1.4	2.4	3.4	Mitigate	Communication of interfaces beforehand, Request interface descriptions from partner BC Ferries beforehand	0
20	sci.-techn.	Risk, that the disturbances caused by the cable connections are significant and cannot be fixed in the available measurement time	1.3	3.0	3.9	Mitigate	Bring spare cables and connections to be able to exchange connections randomly	0
21	sci.-techn.	Risk, that no correlation between URN and vibration can be detected when creating the noise measurement system	1.1	3.0	3.3	Accept	These findings are an important result of the project and determine the direction of future projects	0
22	sci.-techn.	Risk, that an insufficient number of measurements for different operation points is obtained to generate statistically significant data	1.2	1.5	1.8	Accept	Execute double run measurements (two measurements with similar operation condition), Employ correlation approach that is not based on statistics	1
23	sci.-techn.	Risk, that the vessel traffic is too intense at all locations and masks the URN of the target vessel	1.1	3.0	3.3	Accept / Mitigate	Choose location that has the least vessel traffic, If the problem persists the measurements have to be aborted and the campaigns have to be replanned, the vessels have to be released from schedule for a future measurement campaign, Due to the rescheduling of the measurements additional trips are necessary, which means scope of the project has to be reduced	0
24	sci.-techn.	Risk, that the URN measurements do not produce repeatable results for unknown	1.1	1.9	2.1	Accept	Get support from third-party experts during measurement campaign	0

		reasons						
25	sci.-techn.	Risk, that the measured URN of different vessels is not comparable	1.3	1.3	1.7	Accept	These results are important findings of the project, The cause of the discrepancy should be identified	0
26	econ.	Risk, that the wrong target audience is selected for the dissemination of the results and the responsible operators of vessels are not reached	1.2	1.4	1.7	Mitigate	Use extensive history of Transport Canada events to identify target audience, Select dissemination event with the largest intersecting set of targets	0
27	econ.	Risk, that the noise mitigation system is not accurate enough to be accepted, preventing widespread distribution of the system	1.3	2.0	2.6	Accept	This would be an important finding of the project and has to be adressed in future follow-up projects	0
28	econ.	Risk, that the noise mitigation system is too expensive in setting up, preventing widespread distribution of the system	1.2	2.0	2.4	Accept	This would be an outcome that creates a challenge for follow-up projects to reduce the effort for the calibration of the system	0
29	econ.	Risk, that the target case vessel changes owners and the owner does not intend to cooperate for the measurements	1.0	2.2	2.2	Accept	BC Ferries owner is BC Ferry Authority, which is part of the British Columbia government, so a change of vessel is highly unlikely, Conduct measurements with remaining vessels or look for different target cases	0
30	econ.	Risk, that no interface for third-party equipment is available, or additional costs are associated with the preparation of such interfaces	1.3	1.8	2.3	Mitigate	Communication of interfaces beforehand, Request interface descriptions from partner BC Ferries beforehand, Prepare all interface equipment during preparation phase	1
31	econ.	Risk, that measurement equipment and in particular cables are more expensive due to greater length requirements than currently available	1.3	2.0	2.6	Mitigate	Check general arrangement of vessel and calculate cable length beforehand, Procure suitable cables during preparation phase	1
32	econ.	Risk, that the planned manpower for internal post-processing is	1.7	1.2	2.0	Accept	Duration and effort of the task have to be extended under own cost until the	1

		underpredicted.					data is processed, as they are a central component of the project	
33	econ.	Risk, that the engineers experience motion sickness during the measurements	2.0	1.1	2.2	Avoid	Select engineers that are experienced with traveling on sea vessels	0

5 Key Findings

The key findings of the project are listed in the following:

1. URN prediction with on-board vibration data is feasible with errors around $2dB$ in the overall SPL at a vessel speed of $v_s = 18kn$. Spectral accuracy is less with errors of up to $10db$ depending on frequency range and may be increased with better algorithms, which is possible with over-the-air updates. The frequency range representation partly suffers from inaccuracies caused by the general uncertainty in URN measurements, which is part of the training data sets. This may be avoided with a standardized calibration process of HyPNoS outside of normal operation of the vessel, for instance at sea trials.

2. Live processing of vibration data is feasible for a small amount of sensors. Handling the data in frequency domain and processing it on a PLC even considering neural network surrogate models based on common programming languages can be achieved with response frequencies $f_r \approx 1Hz$ in one third octave bands.

3. Simplicity generates market acceptance, even if the results may improve otherwise. The amazing feature that was accomplished in this project out of necessity is that the system in its simplest form requires only an electric connection and internet to give a surprisingly accurate prediction. The system would even work without internet, however, then the results can only be accessed on the integrated screen, which is not possible due to the location of installation on this particular vessel. The next step in complexity, which is in this case minimally required for usability, is the inclusion of an internet connection to be able to access the information from anywhere. Further upgrade possibilities for outputs are bridge panels for user friendliness. For the input as many parameters as possible should be included, as each one increases the accuracy of the system immensely. In order of importance these are:
    a. Rotation rate
    b. Pitch setting
    c. Vessel speed over ground

d. Rudder angle
e. Delivered power
f. Vessel position
g. Vessel speed in water
h. Vessel draft
i. Vessel trim

Environmental conditions such as wind and weather as well as third party traffic may be obtained in the cloud.

4. High fidelity hydrodynamic flow simulations with finite volume method (CFD) are able to predict the acoustic difference between propeller designs. Especially at the blade passing frequencies the differences are easily recognizable in the underwater noise signature. On the hull, pressure pulse evaluations and data based evaluations can reveal excitation patterns of interest to the structure-borne noise analysis and in this case placement of acceleration sensors for the HyPNoS.

5. With CFD simulation results and measurements it is found that for this vessel only one hull sensor provides enough information for the prediction algorithm to work. The addition vibration information parallel to the hull does not benefit the predictive potential of the HyPNoS.

6. The sparse data collected with respect to vessel operation points, prevents efficient usability in general machine learning tools. Physics informed neural networks or special data treatment for sparse data may support the notion of machine learning in future iterations of the system.

7. A simple linear regression between the vibration and URN data achieves good agreement regarding the overall SPL with an accuracy of $\Delta SPL < 2dB$. However, due to the uncertainty in the fundamental training data the spectral accuracy may be improved. It is acknowledged that this is only a prototype implementation that may be updated to more complex mathematical relations in the future.

6. Project Controlling

The updated project work plan with the project management tools is presented in the following. The list of work packages can be found in Figure *33* and Figure *35*. The resource estimation is in Figure *33*, the schedule is given in Figure *34*. The final project burn-down is given in Figure *36*.

The project cost a total of 237.7k$, which means it was 18.9% over the planned budget. The total Transport Canada contribution was 150k$. Please see the document "TC-QVI-I&A-REQUEST_FOR_REIMBURSEMENT_AND_INVOICE_LISTING-SCHOTTEL CANADA INC_2023_1.xlsx" for more details.

Work Package	Duration [m]	Ressources [h]
1. Project Management		
1.1 Project Meetings	<1	0
1.2 Reporting	<2	0
1.3 Dissemination	2	40
2. Development of URN Prediction Tools		
2.1 Validation simulation with latest developed methods	3	45
2.2 Comparison of simulation and measurement	1	10
3. Tests and Trials		
3.1 Preparation of Measurements	1	40
3.2 Acoustic Analysis Propeller Design	2	
3.2.1 Original Propeller Transit/Berthing		60
3.2.2 Improved Propeller Detailed Operation Analysis		60
3.2.3 Improved Propeller Transit/Berthing		60
3.3 Measurement post-processing and evaluation	4	150
3.4 Validation of noise measurement system with improved system	2	
3.4.1 System Tuning On-Board		90
3.4.2 Validation of System in Transit/Berthing		80
4. Noise monitoring system		
4.1 Development of data processing method		
4.1.1 Cross correlation with appropriate measure	4	120
4.1.2 Development of data mapping model	3	90
4.2 Development of real-time monitoring system		
4.2.1 Development of surrogate models for measured parameters	6	200
4.2.2 Implementation in existing software	3	150

Figure 33: Overview of the work packages and associated resources in HyPNoS

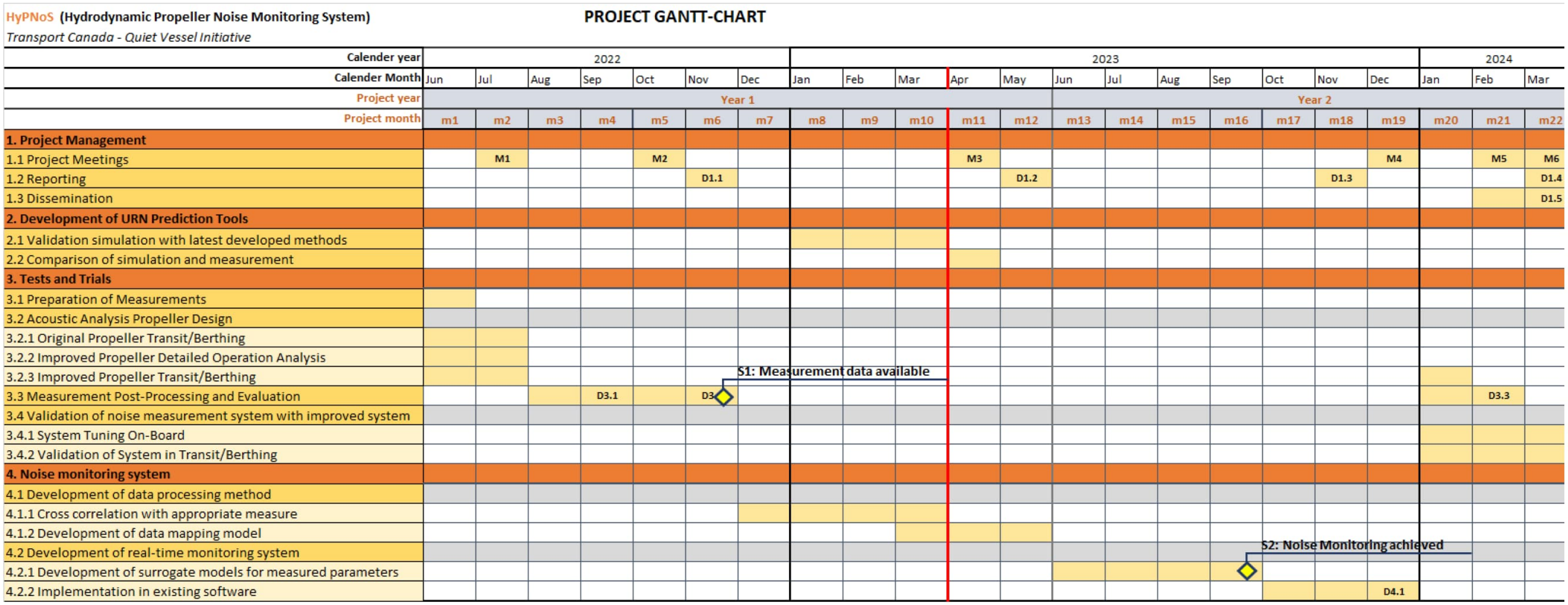


Figure 34: Project Gantt-chart

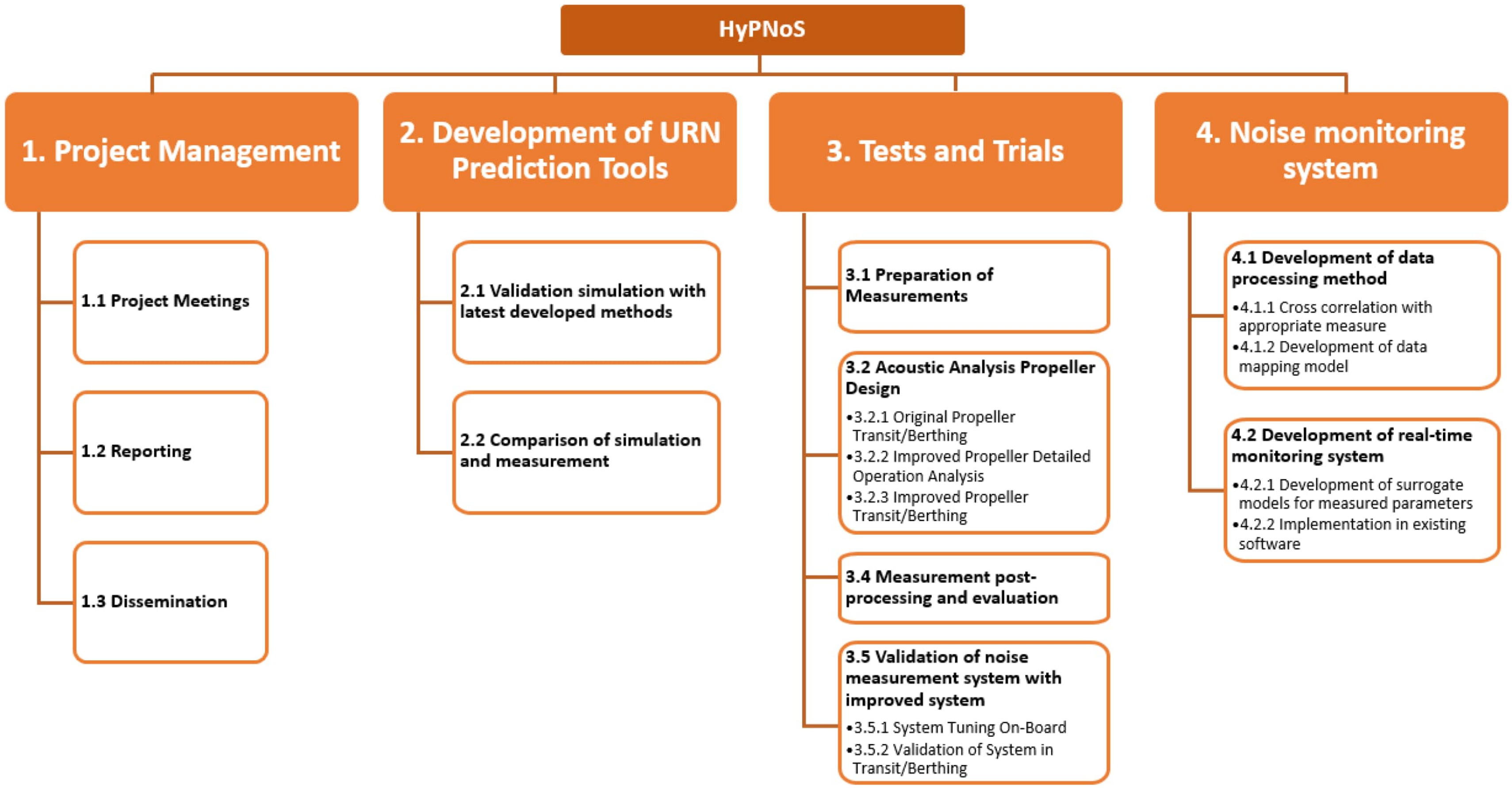


Figure 35: Work breakdown structure

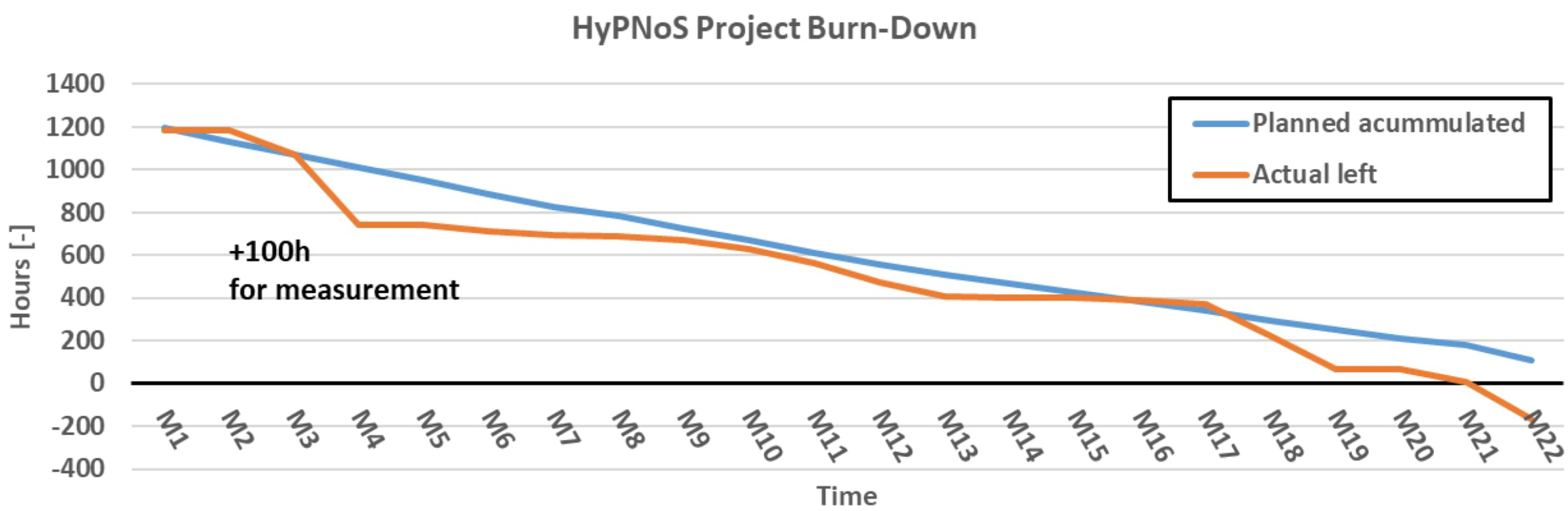


Figure 36: Project burn-down