Noise from ships powered by LNG or electricity and its effects: a cross-domain investigation

Final report of the Silent@Sea project

Swedish Environmental Research Institute

Report number: C 809
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ISBN: 978-91-7883-558-4
Photo: Anders Genell

Ship, noise, airborne, underwater, onboard, working environment, electrical, liquid natural gas (LNG)

Summary

Electrification of ships offers zero-emission travel and is spreading rapidly, and more and more ships are operating on liquid natural gas, LNG, or other alternative fuels. However, the relation between these modern forms of ship propulsion and noise pollution is not generally understood. The Silent@Sea project has investigated this through four case studies, where modern vessels have been measured in different propulsion modes and compared to sister vessels. This has mainly been done in route, which permitted us to gather unique data on the noise radiation of large ships in commercial operation. The project has investigated radiated airborne and underwater noise as well as onboard noise and its impact on work environment and passenger comfort. The results show that the modern forms of propulsion lead to lower noise levels onboard, which are coupled to a better work environment and greater passenger comfort. The radiated airborne noise of electrical hybrid vessels is reduced in battery powered operation at certain low frequencies associated with the diesel engine. The same holds for the radiated underwater noise, but the differences are smaller there, indeed smaller than differences between sister vessels. Finally, a new generation of LNG-powered vessels are found to be quieter than an older generation with similar specifications.

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1 Introduction

Ships transport goods and passengers across rivers, lakes, seas and oceans. In fact, ships carry 90 % of international trade. Shipping has been around for many hundred years and the sector is still growing, with ships becoming larger and the number of ships in traffic increasing. At the same time, the International Maritime Organization (IMO) strategy on reduction of GHG (greenhouse gas) emissions from ships (International Maritime Organization, 2023) states that shipping should reach net-zero GHG emissions by or around 2050, and many nations have implemented national goals on GHG emissions. Moreover, the mandatory energy efficiency design index (EEDI) forces new ships to become more and more energy efficient. These and other policies motivate intense work on reduction of GHG and other emissions.

Electrification of ships offers zero-emission travel and is spreading rapidly. Due to battery limitations, it is best suited for relatively short routes. At longer routes, traditionally used oil and diesel fuels are being replaced by liquid natural gas (LNG), which offers lower emissions. Other fuels including methanol, ammonia and hydrogen are under investigation and we are starting to see their potential in the shipping industry.

Ships are a major source of noise pollution. Underwater noise from ships impacts marine life, airborne noise affects residents living near harbors and shipping lanes, and noise onboard ships impairs the environment for the crew and the passengers.

The present Silent@Sea project report attempts to fill the research gap on the relation between ship noise and propulsion method. *What is the effect of modern ship propulsion on noise radiation and the onboard environment?*

1.1 Aim and problem formulation

The purpose of the Silent@Sea project is to study how modern ship propulsion affects radiated noise and onboard environment, in comparison to conventional propulsion. The project is based on measurements and interviews in typical operating conditions, predominantly in the ships' normal operating routes. These measurements are set up to obtain comparable data that permit isolation of the effects of propulsion mode as well as comparison of different vessels.

1.2 Research overview

Silent@Sea studies airborne, underwater and onboard ship noise as well as how onboard noise affects work and passenger environment onboard. We will now review the state of the art in these fields, focusing on ships with electrical or LNG propulsion. The state of the art in noise measurement methods is described in section 2.

There are a large number of sources of radiated airborne noise from a ship, including the main engines, different types of pumps and a great variety of ventilation systems with powerful fans. Most noise sources are independent of the actual propulsion. In traditional vessels the main engines have, for the last 70 years, been large diesel engines, sometimes referred to as "cathedral" engines due to the size and the row of vertical, tower-like cylinders. The long stroke and low speed of revolution of large diesel engines mean that they radiate high sound levels in the lowest frequency range generally considered with regards to the contribution to community noise. The noise is mainly radiated from the exhaust funnel situated high up above the water surface and, as low frequency sound is not affected strongly by atmospheric absorption, the combined effect is that the low frequency airborne noise from a ship reaches further than other types of transportation noise (Delta A/S, 2006). The World Health Organization issued the latest Environmental Noise Guidelines for the European Region in 2018 where recommendations are given about noise level limits for different modes of transportation to avoid severe noise related health issues (WHO, 2018). The guidelines contain recommendations for road, rail and air traffic, but do not contain recommendations for ships. Neither are there any specific recommendations for low-frequency noise. There are however recommendations for noise from wind turbines and, since it contains relatively high levels of low-frequency noise, it is interesting to note that the corresponding limits are lower than for road or rail traffic. In fact, the limit for wind turbines is the same as for airplane noise, which also contains high levels of low-frequency noise. Airplanes radiate noise in a broad frequency band so there is not just low-frequency noise, but when considering an indoor situation where the noise has propagated through the façade of a dwelling, the higher frequencies have been attenuated more efficiently than the lower frequencies. The fact that ship noise, like wind turbine and airplane noise, is dominated by low frequency noise, suggests that ship traffic close to dwellings should follow the same recommendation as those noise sources. There is a need for more research into the effects of low-frequency noise on human health. A Swedish overview of studies conducted found that, for continuous sounds like compressors or ventilation fans, low frequency dominated noise is more annoying than other types of noise (Persson Waye et al., 2017).

Ship underwater noise affects marine life and can cause both behavioral and physiological effects depending on noise level and frequency distribution. Both marine mammals, fish and invertebrates can be influenced by underwater noise. In a recent review of the environmental effects of man-made underwater noise, ship noise was found to give a significant impact in 95 % of studies (Duarte et al., 2021). An even more recent overview of ecological effects of underwater noise is provided in (Johansson et al., 2023). Propellers and machinery are the dominant sources of ship underwater noise. Commercial ships are designed for fuel efficiency, and an efficient propeller will cavitate, at least to some extent. Propeller noise is therefore often dominant in a ship's underwater noise. Ship underwater noise levels and frequency distribution have been described in several studies, e.g. (Arveson & Vendittis, 2000; Karasalo et al., 2017; MacGillivray et al., 2019; McKenna et al., 2012). The underwater noise radiated by a ship is related to design parameters such as ship length, tonnage, engine power and the ship's block coefficient. However, it cannot be accurately predicted from such parameters; hull and propeller design have a great influence which cannot, at present, be predicted from design information (MacGillivray et al., 2022). There have been few studies on the underwater noise of electrical or LNG fueled ships. A comparison between a 10 m passenger ferry powered by two 4 kW electrical motors and a 25 m ferry powered by two 250 kW diesel engines travelling at the same speed showed that the electrical ferry was quieter (Parsons et al., 2020). However, the diesel-powered ferry was larger and had more powerful engines and may therefore be expected to radiate more underwater noise; the study cannot separate the effects of propulsion mode from the effects of vessel length and engine power. A recent study comparing small recreational vessels with electrical motors to similar vessels with conventional motors also showed that the electrically propelled vessels were quieter (Yori, 2023). The vessels under study were similar in capacity and functions, but not in engine size; the electrically powered vessel had a 5 horsepower (hp) motor, while the conventionally powered vessel had a 50 hp engine. The more powerful engine is most likely much heavier than the electrical one, making the conventionally propelled vessel heavier. A weakness of this study is that a heavier vessel may be expected to need more power to propel it through the water, hence likely producing more underwater noise. This study also suffers from the inability to separate the effects of propulsion from the effects of engine size.

There are many sources of onboard noise on a ship, for example main and auxiliary engines, generators, ventilation and pumps. Some of these sources cause noise that radiate into the environment, and some do not. Machines with moving parts generate vibrations, which may in turn generate noise when vibrating surfaces are in contact with air. A large machine such as the main engine may transmit vibrations to the internal structure or the hull of the ship, which may lead to a more efficient noise generation. Engine mounts that reduce the transmission of vibrations to the structure and hull are available but usually not applicable to the large, low-speed diesel engines that power most of the commercial shipping fleet. The IMO and ship classification societies have published guidelines on acceptable onboard noise levels (International Maritime Organization, 2012). Higher levels are allowed in engine rooms, where hearing protection is typically required, than in engine control rooms, cabins and on the bridge. To the best of our knowledge, there have been no studies of the influence of propulsion mode on onboard noise levels. The effects of engine and propeller operating conditions as well as heating and ventilation on noise inside a cabin were reported by (Borelli et al., 2021). They showed that A-weighting is not sufficient to capture the perceived intensity of the onboard noise due to the presence of strong low-frequency components. A similar study that included noise during maneuvering close to port showed that this may generate particularly high bursts of noise (Borelli et al., 2015). Ship onboard noise was recently reviewed by (Bocanegra et al., 2023).

At sea, having a good working environment is important to achieve a high level of maritime safety, as there can be long distances to various public services such as medical care and rescue services. A good working environment also helps to attract both women and men to professions in the shipping industry. There are many occupational health and safety risks for personnel on board ships. Tasks, technical equipment, methods and organization vary depending on the shipping company, vessel size and vessel type. In a study from 2015 on work environment and safety on Swedish ships, it was concluded that noise, the risk of accidents on board the ship and vibrations from the hull are the major work environment problems, and it was seen as important to work to reduce noise levels (Forsell et al., 2017). The authors have not been able to find any previous studies of how the onboard work and passenger environment is affected by the propulsion mode.

1.3 Participating ships and ship owners

The Silent@Sea project has collaborated with four ship owners, who have offered their time, resources and access to their ships in kind.

ForSea (now Öresundslinjen) operates electrical hybrid RoPax ferries that run between Sweden and Denmark. Their vessels Aurora, Tycho Brahe and Hamlet were studied here. They are sister vessels, except that Aurora and Tycho Brahe have been converted to electrical hybrid propulsion.

Färjerederiet (Trafikverket Färjerederiet) operate road ferries on a fjord crossing in western Sweden. Their vessels Neptunus and Tellus were studied here. They are sister vessels, except that Tellus is an electrical hybrid vessel and Neptunus is conventionally powered.

Styrsöbolaget operates public transport on water in Gothenburg on commission from Västtrafik. The electrical hybrid passenger ferry Elvy was studied here.

Furetank is a Donsö-based ship owner that operates product tankers. Several ships from their modern Vinga series and the older West series are studied here. All vessels in the Vinga series, and some in the West series, can run on either LNG or diesel.

The participating ships and the studies performed on each ship are described in detail in section 3.

2 Methodology

2.1 General

The general methodology of Silent@Sea is designed to obtain data on noise emissions and onboard environment that isolate effects of propulsion mode. This is achieved through two study design choices.

Silent@Sea studies sister vessels, i.e., vessels that are from the same series and thus similar to each other. We seek sister vessels that only differ in propulsion mode, or single vessels that can be operated in different propulsion modes. Additionally, we compare modern vessels to older vessels of similar characteristics.

Noise propagation depends on local conditions such as weather and is difficult to predict to a high degree of accuracy. Moreover, a ship carries a multitude of different machinery that can make noise, and it is difficult to control all this machinery in detail. To reduce uncertainties and variations associated with these factors, Silent@Sea makes simultaneous measurements of each ship across all noise domains. Radiated airborne and underwater noise is recorded on cabled sensors and captured synchronously at the same data collection device. Onboard noise in several different types of environments is recorded during the radiated noise measurements. In some cases, additional onboard measurements are made at a later occasion.

The work and passenger environment studies are based on interviews and questionnaires. The respondents are asked to judge their impressions of the onboard environment in relation to noise and vibrations and the answers are naturally influenced both by current and previous impressions. Therefore, the work and passenger environment studies were executed independently of the noise measurements.

Silent@Sea is based on four case studies, which are described in detail in section 3. Three of the case studies cover electrical hybrid vessels and the fourth covers tankers that can run on LNG or diesel fuel. The three studies on electrical hybrid vessels permit us to draw general conclusions, but there is too little data on the LNG/diesel case to generalize. All ship owners participated in kind and went out of their way to support this study. The authors are grateful for their time and effort, without which it would not have been possible to perform these studies.

The electrical hybrid vessels that were studied operate in ferry trade on short routes. In two case studies, the ships were measured in route, operating on their normal timetable. A measurement track was then established in or near the route, and the ships followed this track at constant speed and in a straight course. In the third case study, the ship operates in a busy river crossing in central Gothenburg, where environmental noise levels were judged too high to permit measurement of its radiated noise. The operator took the ship out of traffic to a secluded measurement site where a measurement track was established. In all these case studies, operational data from onboard logging systems was shared with the project and facilitated interpretation of the results.

The tanker vessels studied here operate in spot trade, implying a short planning horizon. For logistical reasons, we were unable to perform dedicated measurements at such short notice. An unmanned measurement station was established at an island near the main channel into Gothenburg harbour. The station was activated by AIS signals from the vessels under study and recorded airborne and underwater noise during ship passages. The captains were asked to maintain a constant speed and pass at the same distance to the noise sensors. It was however not possible to fully comply with this due to channel features and other traffic.

2.2 Radiated noise

2.2.1 Airborne noise measurement

The international standard ISO 2922 describes a method for measuring airborne noise from seagoing vessels (ISO, 2020). The document states that it is applicable to all types of vessels regardless of speed or size, as long as they can be regarded as a point source at the microphone position at a distance of 25 meters from the vessel. For large ships, a distance of 25 meters would put the microphone below the line of sight to the funnel and considering that there often are several noise sources on the vessel captured simultaneously by the measurement microphone, it is unlikely the vessel will act as a point source at a distance much shorter than the vessel length.

An alternative method for measuring noise from moored ships was developed within the research project NEPTUNES. There the distance between ship and microphone is calculated from the height of the microphone and the height of the funnel by allowing an elevation angle of the top of the funnel from the viewpoint of the microphone of 5 to 20 degrees. Thus, there is always an unobstructed line of sight between source and receiver. In Silent@Sea we have adapted the NEPTUNES measurement method to measuring noise from ships underway by developing a floating microphone mounting platform that can be triple anchored at the appropriate distance from the route or track the vessel of interest will follow, Figure 1.

Figure 1. The 'SilentRaft' floating measurement platform with the ferry Tellus approaching.

The floating microphone mount is equipped with a top lantern and an AIS transponder broadcasting its current GPS position. As AIS also requires a vessel name to broadcast, the floating microphone mount was named "*SilentRaft*", and appeared in the navigation systems aboard the different ships that were measured during the project.

The raft was constructed from four sections of standard truss ordinarily used for stage lighting, forming a circle with a diameter of 3 meters. Under the truss circle were strapped four large buoys to provide floatation. On top of the truss circle was mounted a number of aluminum spars making up a mount for a battery and a mast with two microphone booms. The telescopic mast allowed for adjusting the height of the two microphones which was normally set to 3 meters and 2.3 meters for the two microphones respectively.

The microphones used for measuring airborne noise were two Microtech Gefell MV210 half inch IEPE microphones providing a useful frequency response between 0.5 Hz and 20 kHz.

For each passage of the ship under measurement the time signal was recorded, and one of the microphones was also monitored during each measurement to identify potential sources of disturbance. Before analysis the signals from the two microphones were averaged in order to obtain a higher signal to noise ratio. Depending on source distance and the height of both source and receiver, the level can increase or decrease several dB when the direct sound reaching the microphone interferes with the sound reflected in the surface. The different path lengths compared to the sound wavelength of interest will determine the effect. Averaging of two receivers at different height will reduce the effect.

Each passage recording was then transformed into the frequency domain and the levels within each 1/3 octave frequency band between 20 Hz and 16000 Hz was calculated. In order to make measurements comparable the levels were normalized to a distance of 10 m from the source by assuming point source like behavior and calculating the corresponding level reduction due to spherical radiation, which could be regarded as a simple estimate of source strength. Normally to calculate source strength the sound energy in the entire passage is summed in order to include directivity effects, but since for some of the measurement sites there was some disturbing background noise, only the part of the passage that was just before until just after passing the measurement raft was included in the analysis.

For the Furetank ships the measurement raft was not useful as that method relies on several passes of each vessel along a predetermined measurement track. Instead, a stationary measurement station was established on Böttö in the inlet to the port of Gothenburg. The setup was similar to that of the measurement raft in that there were two microphones at different heights at an appropriate distance from the adjacent fairway. For the Böttö measurement station the microphones used were two IK Multimedia MEMS microphones with a useful frequency range from 20 Hz to 20 kHz. The MEMS microphones are slightly less sensitive but are more rugged than the MV210 microphones used on the measurement raft, which was suitable as the microphones would be exposed to harsh weather for several days or even weeks between ship passages.

2.2.2 Underwater noise measurement

The conventional way to characterize how noisy a ship is under water uses the so-called source strength. This is essentially a metric of how much noise energy is emitted into the environment, but is expressed as the equivalent sound pressure level that would be recorded at a notional distance of 1 m. Several analysis and measurement methods are recommended from various ship classification societies, as well as ISO standard 17208 (ISO, 2016, 2019). However, most of these require the water depth to be at least 100 m, which was not feasible for the measurements in this project. The method used here is heavily inspired by the method used by Bureau Veritas (Bureau Veritas, 2018), as described below.

For the on-site measurements, the underwater noise was measured using three hydrophones mounted in a vertical arrangement. For the measurements of ForSea and Färjerederiet ferries cabled Colmar GP1280 hydrophones were used, enabling real-time monitoring of the recorded noise as well as synchronous recording with the airborne noise. The hydrophones have a built-in 36 dB pre-amplifier, sending an amplified differential signal through the sub-sea cable, which minimizes external disturbances. However, at the measurement of Elvy some equipment had not arrived, so autonomous Ocean Instruments SoundTrap300 recorders were used instead. To monitor the underwater noise during this recording another hydrophone was used, which for simplicity was placed close to the work boat and therefore not used for the analysis. The vertical hydrophone array was placed approximately 100 m away from the planned ship track for all measurements. A sketch of the arrangement can be seen in Figure 2. For the autonomous measurement of the Furetank vessels, only a single AS-1 hydrophone from Aquarian Audio with a 26 dB preamplifier in the water was used. A 20 kg bottom weight was used for all the measurements (Figure 3). The floats were similarly modest, with just a few kg of buoyancy. This allowed the entire hydrophone array to be deployed by hand from a small open boat.

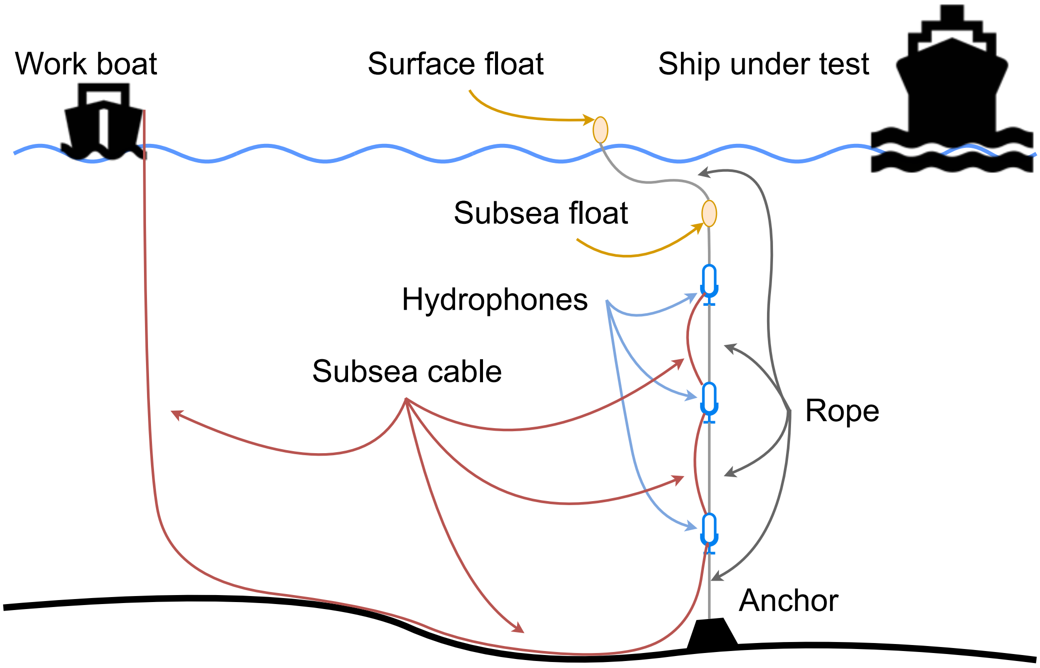


Figure 2. Hydrophone measurement setup.

Figure 3. Mounted hydrophone and bottom weight.

The signals from cabled sensors were recorded using an RME Fireface UCX II audio interface, operating at a 192 kHz sample rate. The hydrophone signals were recorded using differential inputs with no additional gain applied, while the microphone signals were recorded on single-ended inputs with a 12 dB gain.

The acoustic sound pressure at the hydrophones is recorded for all the ship passages, as well as during periods with no sources in the immediate vicinity; these latter act as background noise recordings. For each ship passage, the following processing is performed to quantify the ship noise radiation.

1. The recorded signals are transformed to a time-frequency representation, giving the power spectral density in the 1/3 octave bands from 10 Hz to 50 kHz, in time steps of 1 s. This is done from a 2 s long Hann-windowed FFT representation of the time signal at each 1 s time step.
2. The time-dependent 1/3 octave band levels are compensated for background noise. If the signal-to-noise ratio is less than 3 dB, that particular value is regarded as not valid and discarded from further analysis.
3. The time-dependent 1/3 octave band levels are divided into 19 smaller time segments. Each segment covers a 15° angle as seen from the hydrophone array, placing segments at 5° steps from -45° to +45°.
4. The time-dependent 1/3 octave band levels within each angle segment are averaged in time and compensated for the propagation loss, using the seabed critical angle method as the propagation model (MacGillivray et al., 2023). This yields 19 values of the source level in each 1/3 octave band for each of the three hydrophones, for each passage of the ship under test.
5. The 1/3 octave band source levels are power-averaged between the three hydrophones, and level-averaged over the angle segments, for a 1/3 octave representation of the source level in each passage. The final source level is calculated by level-averaging the individual passages.

This method uses the seabed critical angle method to compensate for the propagation loss, which means that the result is a monopole source level. However, this does not accurately depict how much noise is radiated into the surrounding water, since there is a strong interaction with the water surface. We have chosen to compensate this surface effect in the manner outlined in ISO 17208-2 (ISO, 2019), converting the results into a radiated noise level instead of a source level, by applying a frequency dependent conversion level.

2.2.3 Noise source identification

The aim of the noise source identification performed in this project was to find where the radiated noise originated. This was mainly done by studying the presence of strong tonal components in the radiated noise, both in air and in water. For the case studies with multiple propulsion modes on the same vessel, often some tones were only present in one of the modes revealing their source as related to the difference between the modes. As an example, several distinct tones from the diesel generator could be seen in the underwater Elvy measurements.

First, the recorded sound pressures in a 15 s region around the closest point of approach were selected. These were converted into 0.2 Hz resolution spectra, averaging five time windows each with a 5 second length. The source identification is computed based on the average spectra for each operating mode, using conventional peak identification algorithms to extract the tonal components.

As a second step, when the tones could not be identified through the propulsion mode, the frequencies of these tonal components were matched to known operating frequencies of machinery onboard the ship, e.g., the rotation rate of the engine or the propeller. These operating frequencies were mainly gathered from two sources, either integrated onboard monitoring systems, e.g., Blueflow, or accelerometers mounted for the measurement only. Since the accelerometers could not feasibly be connected to the same recording system as the radiated noise, we deployed simple 3-axis acceleration loggers developed by Axivity. When analyzed, the vibration measurements had too many strong frequency components to properly inform the operating speed of the machine, hence these frequencies were taken mostly from the onboard monitoring systems.

Typically, the noise comes from some part of the propulsion machinery, but there can also be noise from secondary machinery. One useful way to determine if a tonal component comes from the propulsion or not is to perform measurements at multiple sailing speeds. The tonal components can then be compared in the two speeds; components that do not shift appropriately in frequency are not from the propulsion machinery.

To quantify the results of this analysis, the noise power from the identified sources was calculated and related to the total noise power. The tonal components at high frequencies are very densely spaced, which causes larger uncertainties as to what tonal component belongs to which source. Therefore, we have only performed this quantification in the lower frequency range, where the tonal components could be attributed to individual sources with reasonable certainty.

2.3 Onboard noise measurement

Onboard measurement of airborne noise was conducted in a number of compartments in the participating ships. The circumstances for the measurements were very different for the different case studies. There was usually a limited time available for measurements, complex room geometries, limited access to rooms, and little control over additional sound generating activities. Hence, a practical method had to be used. It was inspired by the measurement standard ISO 16032 (ISO, 2004), but with the main goal to provide comparable measurements for the different propulsion modes rather than absolute, standardized, values of the sound pressure level in the measured rooms. The procedures for each case study are described in the corresponding appendix.

The aim was to conduct measurements of airborne noise onboard at the same time as the exterior noise measurements (airborne and underwater). This ambition could in practice only be implemented in one of the case studies. All onboard noise measurement were, none the less, performed during steady state travel to receive comparative measurements between the propulsion modes.

The Swedish Work Environment Authority provides limit values and recommendations of occupational noise exposure (Arbetsmiljöverket - Swedish Work Environment Authority, 2005). These are used in the present work for comparison, while keeping the limitations of the measurement in mind. Primarily, the work environment must not damage your hearing function. If there is a risk to be exposed to 80 dBA equivalent level over an eight-hour working day, the employer must provide hearing protection. If the exposure is 85 dBA, hearing protection must be worn.

Apart from directly damaging exposures, noise can be disruptive, annoying and it can mask information. It can also make you tired and less motivated. There are large individual variations of when a sound environment starts to become a work environment problem. It depends on how demanding and complex a task is for a person, in addition to his/her stress-level and possibility to recover and rest. Low-frequency noise is expected to be dominating in a ship. It can lead to fatigue and drowsiness but can also be disruptive in certain situations (Hygge et al., 2013)

The third octave band results of the measurements in the Appendix are provided together with a reference-curve, "Ref". According to the Swedish Work Environment Authority, these values can be used as guidance when assessing the risk for disruption of low-frequency noise for working conditions with high demands on continuous concentration (Arbetsmiljöverket - Swedish Work Environment Authority, 2005).

2.4 Work and passenger environment

2.4.1 Work environment

The investigation of how a modern propulsion affect the work environment was conducted through semi-structured in-depth interviews, either digitally via Teams meetings or through in-person meetings.

The interviewer took notes and recorded all interviews (after obtaining approval from the interviewees). The conversations lasted between 15 to 60 minutes.

The questions were developed in collaboration with occupational health experts at IVL Swedish Environmental Research Institute and were approved by the shipping companies. The analysis of the results was inspired by qualitative content analysis.

The questions were available in Swedish and, for Furetank, also in English. An English translation of the questions is given below.

Interview Questions

1. Tell me about you, your position onboard the ship and your duties.
2. What is your background and your job experience?
3. Describe your experience of the working environment on board, especially in terms of noise and vibrations.
4. Do you see any occupational health risks and what is your overall perception of the work environment?
5. Do you have any suggestions for improvements?

2.4.2 Passenger environment

The investigation of how a modern propulsion affects the passengers’ experiences of noise and vibrations was conducted through questionnaires. Three out of four participating ship owners run passenger traffic and were included in this part of the project. The questions were formulated in dialogue with the ship owners.

The forms were mostly digital meaning that the passengers scanned a QR-code with their mobile phone and were directed to a web-based survey. There was also a possibility to fill in a paper version of the form.

The passenger study was conducted during one day for each case study, between 07:00–17:00. Different QR-codes were provided during hybrid and electrical propulsion to be able to separate the propulsion modes in the analysis.

The questions were formulated in Swedish. A Danish version was also provided in one of the case studies. An example of the original Swedish version is provided in the appendix. A translated version of the questions is given in the following:

If you consider your experience of your current journey - Circle your response:

How do you perceive the noise level from the ferry itself?

Very low/Not disturbing	Rather low/ Slightly disturbing	Neither or	Rather high/ Disturbing	Very high/ Disturbing	Have no opinion
1	2	3	4	5	0

How do you perceive the vibrations from the ferry itself?

Very small/Not disturbing	Rather small/ Slightly disturbing	Neither or	Rather large/ Disturbing	Very large/ Disturbing	Have no opinion
1	2	3	4	5	0

How satisfied are you overall with the onboard comfort in terms of noise and vibrations on this journey?

Very dissatisfied	Rather dissatisfied	Neither or	Rather pleased	Very pleased	Have no opinion
1	2	3	4	5	0

Some questions about you:

How often do you travel on this ferry?

- ☐ More seldom
- ☐ 1–3 days per month
- ☐ One day per week
- ☐ 2–4 days per week
- ☐ 5–7 days per week
- ☐ Don’t know

What your main purpose with this journey?

- ☐ To/from work
- ☐ To/from school

- ☐ Business travel
- ☐ Leisure trip
- ☐ Tourism
- ☐ None of the above

- ☐ **Age**? _______years

Are you?

- ☐ Female
- ☐ Male
- ☐ Other
- ☐ Do not want to share

3 Case studies

The Silent@Sea project is built around its four case studies. This section presents these, including participating ships, the studies performed on each ship, and the measurement sites.

3.1 ForSea – electric hybrid RoPax vessels

The ships

ForSea operates the ferry transit between Helsingborg in Sweden and Elsinore in Denmark. At 2.76 nm, this is where Öresund is at its narrowest. The crossing takes 20 minutes all in all and is operated day and night using five RoPax ferries. Three of the ferries, Hamlet, Aurora and Tycho Brahe, built between 1991 and 1997, are nearly identical sister vessels. In the 2010s, a decision was taken to convert Aurora and Tycho Brahe to electric hybrid vessels by installing batteries and a rapid charging system in the two ports used by the vessels. At their 2018 inauguration as electric hybrid vessels, Aurora and Tycho Brahe were the world’s largest battery ferries. The new technology cut emissions by about 65 per cent or the equivalent of 23,000 tonnes of carbon dioxide per year. Figure 4 shows a photo of Aurora and Table 1 gives some key data of the ForSea ferries and their drive trains. Note that Aurora and Tycho Brahe have different propellers.

Figure 4. M/S Aurora.

Table 1. ForSea vessel information.

Vessel data	Aurora	Tycho Brahe	Hamlet
Propulsion	Electric hybrid	Electric hybrid	Diesel
Built	1992	1991	1997
Length	111m	111m	111m
Width	28m	28m	28m
Depth	5.5m	5.3m	5.3m
Engines	Four low-speed diesel engines, 2,460 kW each	Four low-speed diesel engines, 2,460 kW each	Four low-speed diesel engines, 2,460 kW each
Batteries	4,160kWh	4,160kWh	-
Propulsion	Four 1500 kW thrusters, two fore and two aft, of which three were operating during our trials	Four 1500 kW thrusters, two fore and two aft	Four 1500 kW thrusters, two fore and two aft
Power generation	An electrical motor drives each thruster. The motor can be powered either by a diesel generator or by power from the batteries.		One diesel engine powers each thruster through a shaft.

Studies performed

The studies performed on ForSea vessels by the Silent@Sea project are summarised in Table 2.

Table 2. Studies performed on ForSea vessels.

Study type	Aurora	Tycho Brahe	Hamlet
Working environment	Yes		
Passenger environment	Yes		Yes
Onboard noise	Yes	Yes	
Onboard vibrations	Yes	Yes	
Radiated airborne noise	Yes	Yes	
Radiated underwater noise	Yes	Yes	

Measurement site

The ForSea measurements were performed in the busy strait of Öresund, between Sweden and Denmark. The location was 800 m southwest of the southern inlet to the central marina and ForSea ferry terminal in Helsingborg.

Figure 5 shows a chart of the area, indicating received GPS locations of the vessels during recording of radiated noise data and the positions of the SilentRaft and the hydrophones. Measurements were only made on westbound passages; eastbound passages used the northern inlet to the ferry terminal and thus passed some 900 m from the measurement area. Figure 6 shows a photo of the measurement site, taken from Tycho Brahe as she made a run in the measurement track. The depth at the measurement site was 25-30 m, there were almost no waves during the measurements and average wind speeds were below 3 m/s with gusts of about 5-6 m/s. The wind was coming from northeast which means in the direction from the receiver towards the source. Ideally the wind should blow towards the receiver from the direction of the source but since the wind speeds were very low it can be considered of less importance in this case.

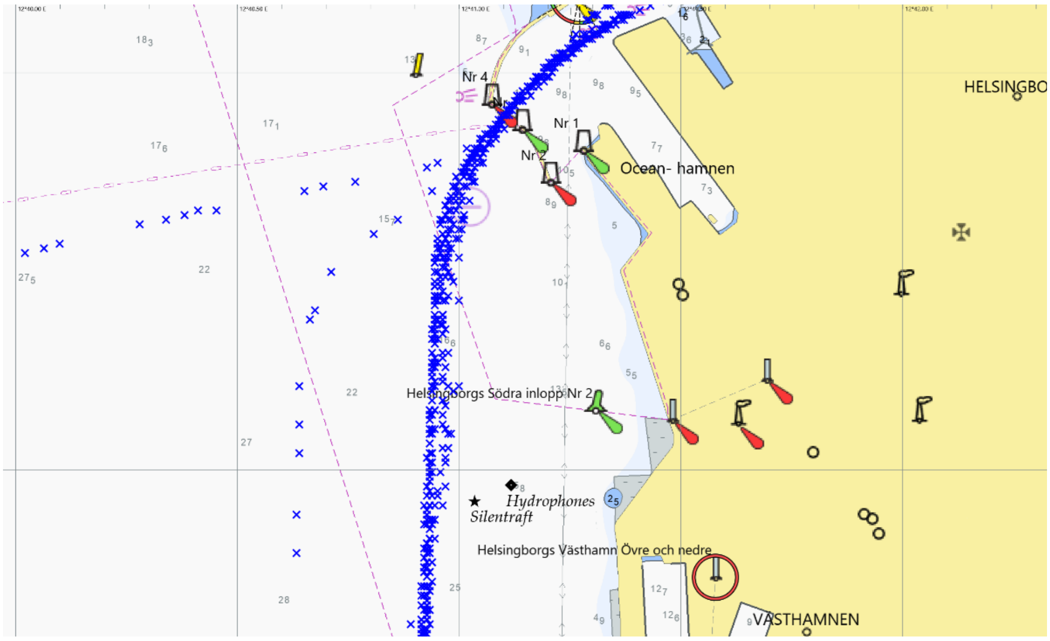


Figure 5. Chart of the Oresund measurement site.

Figure 6. Photo of the Öresund measurement site, showing the anchored data collection boat and the SilentRaft.

3.2 Färjerederiet – electric hybrid road ferries

The ships

Färjerederiet operates Sweden's road ferry system and is working on putting more and more electrically propelled ferries into traffic. The Gullmarn road ferry crossing is 1.0 nm long and the transit time is ten minutes. Currently, the Gullmarn ferry route is served by the two ferries Neptunus and Tellus (Figure 7). Tellus is a sister vessel of Neptunus except that she was retrofitted as an electric hybrid vessel (Table 3).

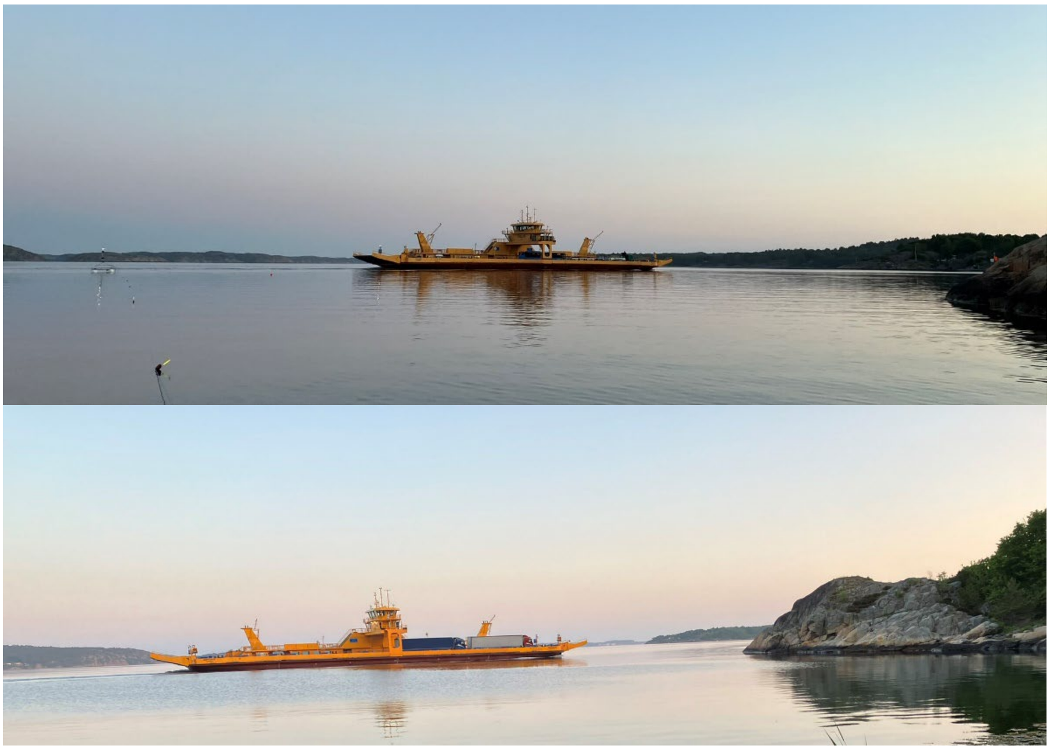


Figure 7. Tellus (top) and Neptunus (bottom).

Table 3. Färjerederiet vessel information.

Vessel data	Tellus	Neptunus
Vessel type	Electric hybrid	Diesel powered
Built	2019	2017
Length	100 m	100 m
Width	18 m	18 m
Depth	2.1m	2.2 m
Engines	Four 478 kW diesel engines/generators	Four 478 kW diesel engines
Batteries	2x475 kWh	-
Propulsion	One 956 kW Rolls-Royce azimuth thruster at each end	One 956 kW Rolls-Royce azimuth thruster at each end
Power generation	Each diesel engine is fitted with a generator. Engines are run at optimal speed and can be turned off individually when not needed.	The diesel engines are connected in pairs to a shaft at each end of the ferry. The shafts power the thrusters.

Studies performed

The studies performed on Färjerederiet vessels by the Silent@Sea project are summarised in Table 4. The measurements of onboard noise, radiated airborne noise and underwater noise were conducted simultaneously with a constant speed of revolution for both propellers of 240 rpm. Measurements of radiated airborne noise and underwater noise were additionally conducted at a constant 190 rpm for both propellers. Furthermore, we made measurements of radiated airborne noise from Tellus when she was turned so that the funnels were facing the microphones.

Table 4. Studies performed on Färjerederiet vessels.

Study type	Tellus	Neptunus
Working environment	Yes	Yes
Passenger environment	Yes	Yes
Onboard noise	Yes	Yes
Onboard vibrations	Yes	Yes
Radiated airborne noise	Yes	Yes
Radiated underwater noise	Yes	Yes

Measurement site

The Färjerederiet measurements were performed in the Gullmarn fjord, on Sweden’s west coast. The location was 500 m east of the Finnsbo ferry stop. Figure

8 shows a chart of the area, indicating GPS locations of the vessels under study and the positions of the SilentRaft and the hydrophones. Measurements were made at night, when only one ferry was in operations. Figure 9 shows a photo of the measurement site, taken from the shore-based data collection site. The depth at the measurement site was 30-60 m, there were no waves during the measurements. The is no meteorological measurement station nearby the Färjerederiet ferry route but considering that wind speeds at the Måseskär lighthouse out in the open sea 25 km to the southwest were below 3 m/s, the actual wind speed at the sheltered site of measurements can be considered to have been 0 m/s for the duration of the measurements.

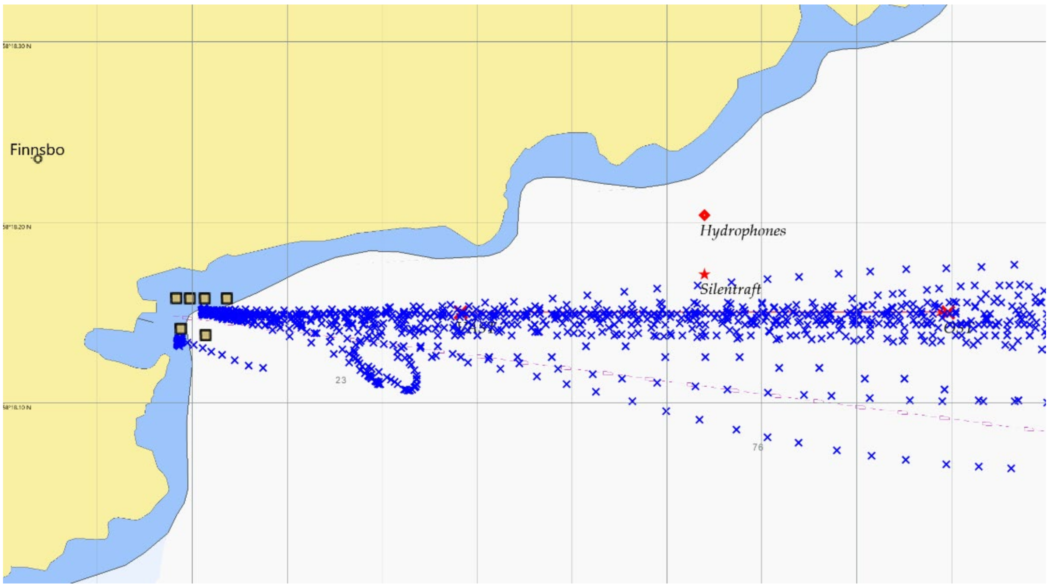


Figure 8. Chart of the Gullmarn measurement area.

Figure 9. The Gullmarn shore-based data collection site and a passing vessel in the measurement track.

3.3 Styrsöbolaget – electric hybrid passenger ferry

The ship

Styrsöbolaget operates Gothenburg's public transport system on water. In central Gothenburg, the 8-minute Göta Älv crossing is implemented by small passenger ferries. Among them are the electric hybrid vessels Elvy and Eloise. Due to high levels of environmental noise, it would not have been possible to perform measurements of radiated noise in route. Styrsöbolaget gracefully offered to take Elvy (Figure 10; Table 5) out of service for a day in order to make measurements feasible.

Figure 10. The Styrsöbolaget ferry Elvy.

Table 5. Styrsöbolaget vessel information.

Vessel data	Elvy
Vessel type	Electric hybrid
Built	2018
Length	33 m
Width	9 m
Depth	1.4 m
Engines	One Scania DI09 257 kW diesel generator
Batteries	2x540 kWh battery pack
Propulsion	One 225 kW Rolls-Royce azimuth thruster at each end
Power generation	The thrusters are driven by electrical motors, which can be powered either by the batteries or the diesel generator.

Studies performed

The studies performed on Styrsöbolaget's Elvy vessel by the Silent@Sea project are summarised in Table 6.

Table 6. *Studies performed on Styrsöbolaget's Elvy vessel.*

Study type	Elvy
Working environment	Yes
Passenger environment	Yes
Onboard noise	Yes
Onboard vibrations	Yes
Radiated airborne noise	Yes
Radiated underwater noise	Yes

Measurement site

Elvy measurements were performed near the island of Donsö, in the Gothenburg archipelago (Figure 11). Figure 12 shows a chart of the area, indicating the measurement track used for recording of radiated noise data and the positions of the SilentRaft and the hydrophones. Radiated noise was measured on both west- and eastbound passages. The depth at the measurement site was 15-30 m. Measurements were done during a beautiful spring day with very small waves, a temperature of 12-18 degrees and wind speeds measured at the lighthouse Vinga on the western edge of the archipelago below 5 m/s. The wind direction was from the north-northeast again meaning a direction from the receiver towards the source, but since the measurement site was then also leeward of Donsö, the wind speeds at the site can be considered to have an insignificant impact on the measurement results.

Figure 11. The Donsö measurement site for Elvy noise measurements.

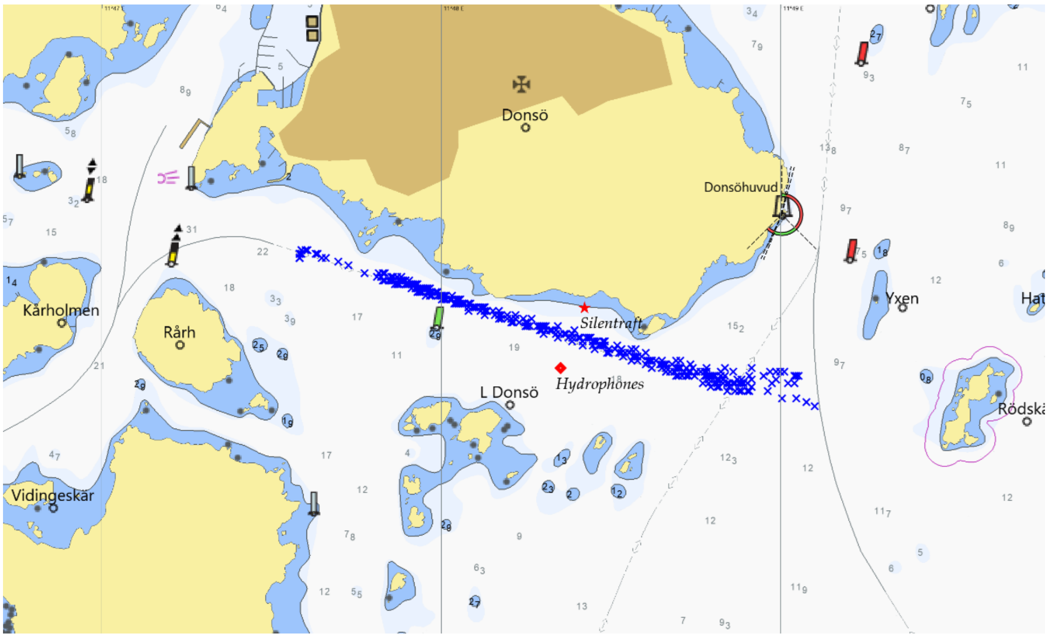


Figure 12. Chart of the Donsö measurement area.

3.4 Furetank – product tankers

The ships

Furetank is a Swedish shipping company focussed on product and chemical tankers under 20,000 dwt. They currently (November 2023) own 20 vessels and have placed orders for 9 additional tankers of their modern Vinga series. Furetank devotes a lot of effort to reducing their environmental impact, and many of their vessels are powered by LNG (Liquid Natural Gas). Within the Silent@Sea project, we have studied a number of Furetank vessels, powered by diesel or LNG (Figure 13; Table 7).

Figure 13. Fure Viten of the modern Vinga Class (top; photo: Furetank) and the older vessel Fure West, which has been upgraded to LNG propulsion (bottom; photo: Furetank).

Table 7. Furetank vessel information.

Vessel data	Fure Viten	Fure Vinga	Ramanda	Fure West	Ramona
Vessel type	Dual fuel				
Built	2021		2018	2006	2004
Length	150 m			144 m	144 m
Width	23 m			22 m	22 m
Gross tonnage	12763	12763	12770	11719	11548
Engines	4500 kW low-speed diesel engine			6190 kW low-speed diesel engine	
Propulsion	Conventional: single propeller on a shaft that is turned by the engine				
Fuel	LNG or diesel				

Studies performed

The studies performed on Furetank vessels by the Silent@Sea project are summarised in Table 8.

Table 8. Studies performed on Furetank vessels.

Study type	Fure Viten	Fure Vinga	Ramanda	Fure West	Ramona
Working environment	Yes				
Onboard noise	Yes				
Onboard vibrations	Yes				
Radiated airborne noise		Yes	Yes	Yes	Yes
Radiated underwater noise		Yes	Yes	Yes	Yes

Measurement site

The Furetank tankers studied in the Silent@Sea project operated in so called spot traffic, meaning that planning horizons were short. That necessitated a different measurement approach than applied for the electrical hybrid vessels. An autonomous measurement station was designed, built and placed on the island of Böttö, in the main channel into the port of Gothenburg. The measurement station was triggered by AIS signals from the ships under study and recorded radiated noise when any of them passed. It was deployed during April and May of 2023. Figure 14 shows a chart of the area, indicating position traces of the vessels that we recorded, the positions of the hydrophone as well as the Böttö island where the microphones were placed. The depth at the measurement site was 20 m. A photo of the measurement site is given by Figure 15.

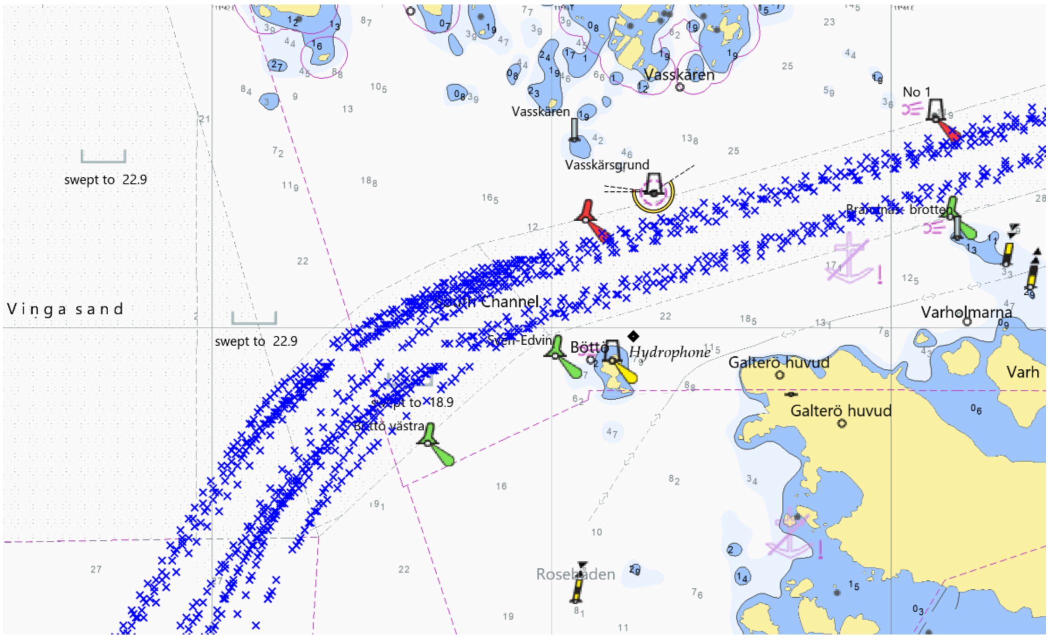


Figure 14. Chart of the Böttö measurement site.

Figure 15. The Böttö measurement site.

4 Results

This section summarizes comparative measurement results. Absolute measurement results can be found in the appendices under each case study.

4.1 Radiated noise

4.1.1 Airborne noise

Figure 16 shows the differences in normalized 1/3 octave band sound pressure level between hybrid and fully electric modes of propulsion for individual ships. The different frequencies of the level difference peak values correspond well to what would be expected results from the difference in engine size between the ships with larger engines that turn at slower speeds of revolution mean lower fundamental frequency. The difference is smallest in level and lowest in frequency for Aurora, having the largest engine of the three ships in the comparison, whereas the level difference is highest for Tellus when turned so that the funnel points towards the microphone, at a higher frequency corresponding to a smaller engine size. The frequency of the peak level difference for Elvy is the highest, corresponding to the smallest engine and the peak level difference is larger than for Aurora and also larger than for Tellus with the funnels facing away from the microphones. For Aurora there seems to be some broadband noise when running in hybrid mode that shows as an overall level increase in most frequency bands when compared to fully electric mode. The reason for this is not established but a hypothesis could be that there are cooling fans for the diesel engines running when operating in hybrid mode and the exhaust vents for these fans are radiating broadband noise. The same can, to a lesser degree, also be observed for Tellus when turned with the funnels pointing toward the microphones. In the case of Tellus, it is likely that some ventilation exhausts that are active in both modes of operation face the same direction as the funnels so that some more broadband ventilation noise was recorded when that side was facing the microphones. As the recording conditions during the Färjerederiet measurements were ideal, being dead calm during measurements, those measurements should be particularly reliable.

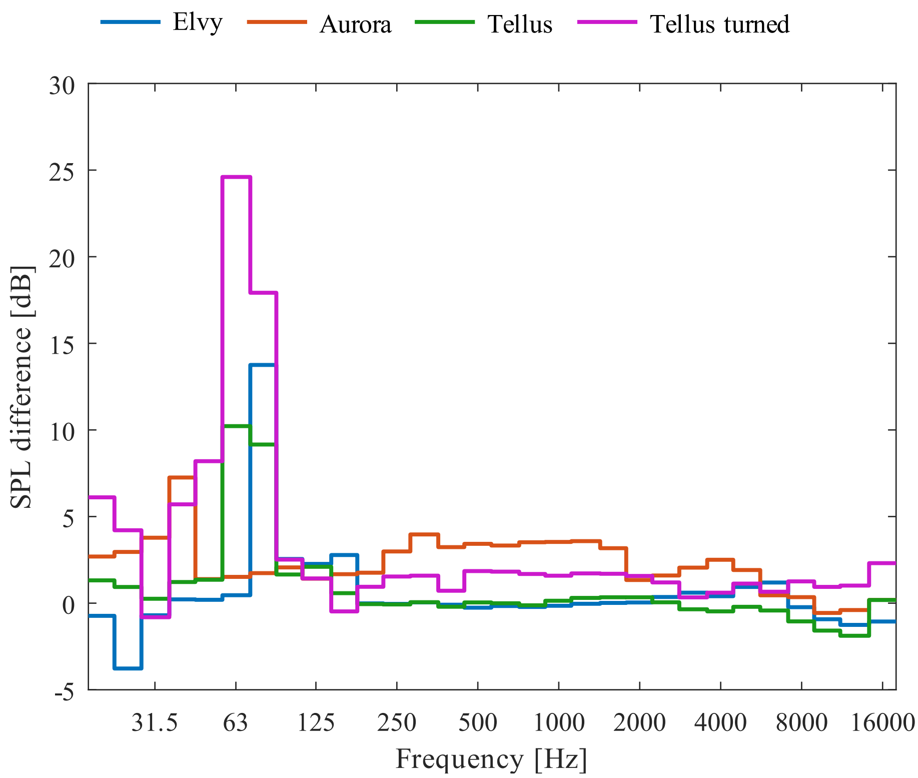


Figure 16. Differences in 1/3 octave band levels between hybrid propulsion and fully electric propulsion for three different ships. The magenta curve represents Tellus turned with the funnels facing towards the measurement microphones.

Table 9 summarizes the peak 1/3 octave band levels and the corresponding maximum level differences for each ship. It can be noted that rotating Tellus so that the funnels face the microphones increases the peak level difference a further 14 dB when comparing hybrid mode to fully electric.

Table 9. Most prominent 1/3 octave band levels and level differences at corresponding center frequencies for hybrid compared to electric propulsion mode in three vessels.

Ship	Frequency [Hz]	Peak hybrid level [dB re 20 µPa]	Level difference [dB]
Elvy	80	67.5	13.8
Aurora	40	88.9	7.3
Tellus	63	71.4	10.2
Tellus rotated	63	90.8	24.6

Figure 17 shows a comparison of sister vessels running in hybrid mode. The difference spectra happen to look very similar for both pairs of sister vessels which is surprising considering the difference in size and construction between the ForSea ships and the Färjerederiet ships. It is mainly for some of the lower frequency bands corresponding to engine noise that the sister vessels differ, but there also seems to be some increased broadband noise in the higher frequency range from Tellus compared to Neptunus. Aurora was running on three out of four thrusters during the measurements whereas Tycho Brahe was running on all four, which could explain some of the differences between the two sister ships. Tellus and Neptunus have the same type and same number of engines but still exhibit differences in radiated noise similar to that for Aurora – Tycho Brahe.

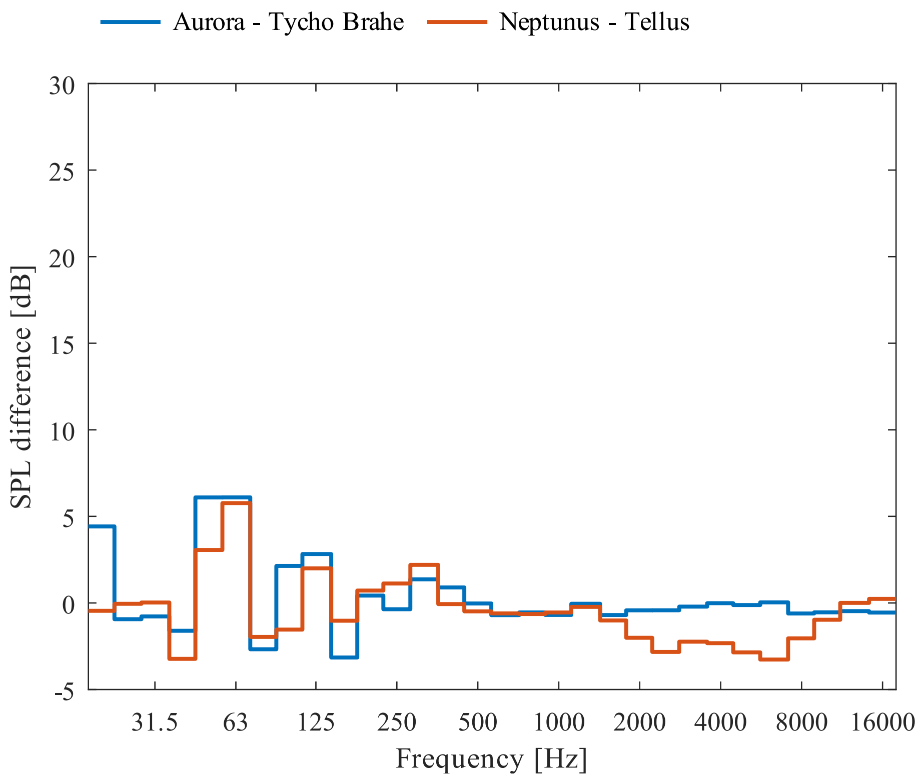


Figure 17. Differences in 1/3 octave band airborne levels between sister vessels under hybrid propulsion.

As most of the recorded passages by Furetank ships at the Böttö measurement station were masked by wind noise, a similar comparison between sister vessels was not possible to achieve for airborne noise.

4.1.2 Underwater noise

The propulsion mode comparisons done in this project allowed for a very controlled separation of the radiated noise output from the diesel generator. As shown in Figure 18, disabling the generator typically does not lower the underwater noise output significantly. The exception is Elvy at the 1/3 octave bands centered at 125 Hz and 160 Hz, where the generator increases the underwater noise radiation by around 10 dB.

A clearer difference can be seen in Figure 19, comparing the sister vessels included in the project. It should be noted that the differences shown here likely do not have the same causes. During the measurement, Aurora was running with three thrusters compared to the four thrusters on Tycho Brahe (and Aurora's normal configuration). Removing one thruster will increase the loading on the individual thrusters, and the increase in noise output from this additional loading is larger than the 25% reduced by removing one thruster. The comparison between the Vinga series of tankers and the West series of tankers indicate that the newer ships are somewhat quieter. However, only a few ships have been measured and under less controlled conditions than the other studies in the project. Finally, comparing the hybrid Tellus with the conventional diesel powered Neptunus also indicates that the ship with more modern propulsion is quieter. These two ships are very similar, with the same propeller and hull design. However, the overall status of the ships was not investigated, which could also be a contributing factor to the differences.

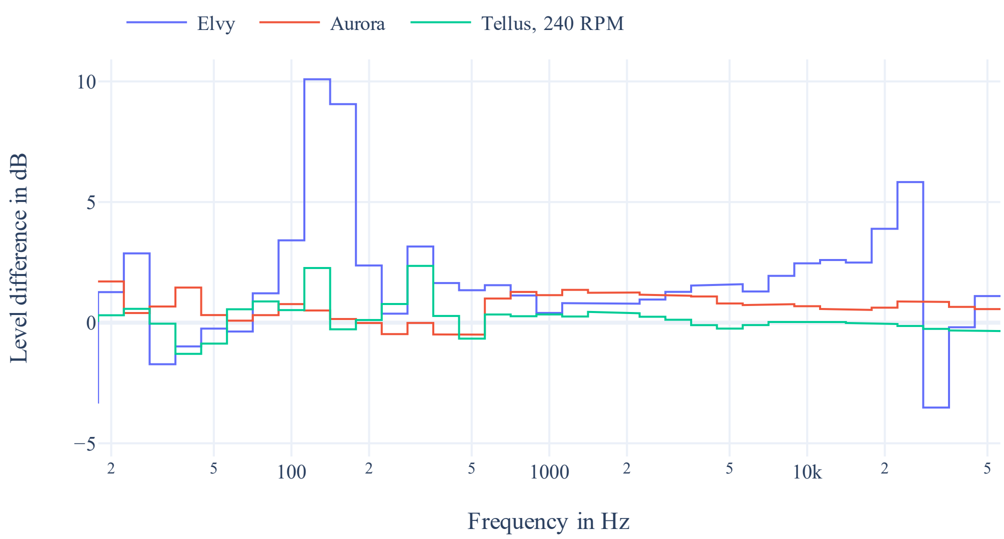


Figure 18. Difference in hybrid and fully electric mode, for the vessels that have more than one propulsion mode.

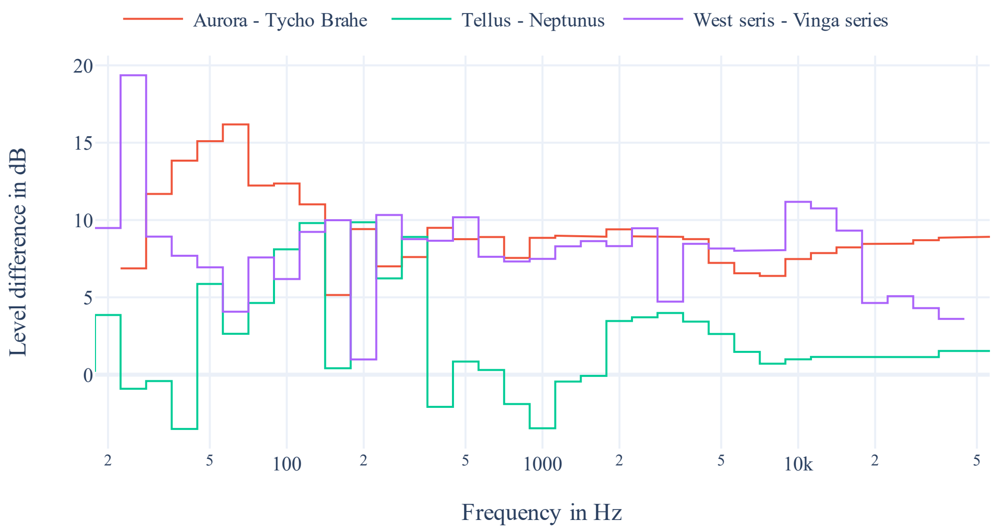


Figure 19. Differences between similar vessels. The Forsea vessels are compared in hybrid mode, the Färjerederiet vessles in Hybrid/Diesel modes, and the Furetank vessels in diesel mode.

4.1.3 Noise source identification

The power distributions of the identified tones are shown in Figure 20 for three of the hybrid ships: Elvy, Aurora, and Tellus. These results are in the form of the relative noise power from each of the identified sources, which is different from the decibel levels used elsewhere in the report. To relate the two metrics, a comparison between level reduction and percentage reduction is given in Table 10; a substantial level reduction requires a much larger reduction in power than the metrics might suggest.

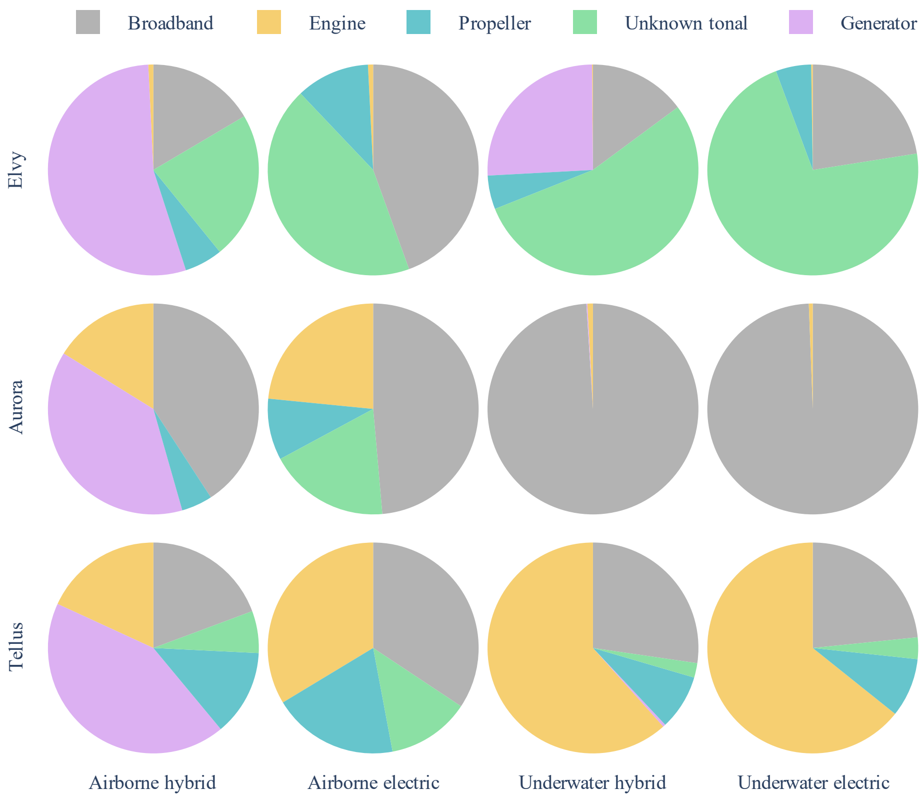


Figure 20. Noise source power distributions for select ships from the case studies. Note that the diagrams represent linear power, not logarithmic levels.

Table 10. Level reduction and corresponding power reduction.

Level reduction	Power reduction
1 dB	20 %
3 dB	50 %
10 dB	90 %
20 dB	99 %

Common to all the hybrid cases is that the onboard diesel generator contributes with approximately 50 % of the airborne noise power in the studied frequency range of 10 Hz to 250 Hz. This indicates that sailing on battery power should reduce the low frequency noise levels by approximately 3 dB. In every investigated case there are contributions related to the propeller blade passing rate that radiate in air. This is likely caused by pressure pulses from the propeller exciting the hull of the ship, which then radiates into the air. However, these tones are of such a low frequency in the human range of hearing that they are usually not included in typical airborne measurements.

The Aurora results are dominated by a strong broadband component in the water. This is likely from substantial cavitation at the propeller, which is known to generate mostly broadband cavitation. Of further interest is also the results from Elvy, where a large portion of the noise power comes from strong tonal components that do not match the operating frequencies of included machinery. Since the trials were only performed at a single speed, it is not possible to determine if this is coupled to the propulsion system or a separate machine.

It is interesting to note that the diesel generator is not seen in the identified underwater noise tonals from Aurora and Tellus when running in hybrid mode. This means that its vibrations do not generate sufficiently strong tonals to be represented in this analysis.

4.2 Onboard noise

This section summarizes the comparative measurement results of equivalent sound pressure level in different compartments onboard.

Table 11 gives an overview of the differences in A-weighted total level between two propulsion modes for the measured rooms. The differences can be further studied in the graphs in Figure 21-Figure 25, where the propulsion-mode-difference of sound pressure level in 1/3 octave frequency bands (1/3 octave bands) are shown.

As expected, the largest differences between propulsion modes are found in the **engine/generator rooms**, where up to 30-40 dBA change is measured for electrical hybrid vessels. For Fure Viten a 3 dBA difference is found between diesel and LNG propulsion. The spectral differences can be seen in Figure 21. The ForSea ferries have a variation of a 10-30 dB decrease in single frequency bands between hybrid and electric mode up to 400 Hz. Above this frequency, the difference is more stable, and above 1000 Hz the difference decreases slowly. For Tellus there is a similar trend, but the difference between hybrid and electric propulsion grows even more with frequency. This suggests that there is a surprising high frequency generating component (>1000 Hz) connected to the operation of the diesel generator. The difference between LNG and diesel propulsion for Fure Viten is both positive and negative, i.e., in a few of the lower frequency bands, LNG is louder. However, in a large part of the spectrum, from 315 Hz to 2500 Hz, the diesel propulsion is louder by 1-4 dB.

In the **engine control room,** there is a 2-5 dB difference in the A-weighted sound pressure level. The spectral differences can be studied in Figure 22. Interestingly there is a clear variation between the ForSea ferries, where Tycho Brahe seems to benefit more from the electric propulsion compared with Aurora across most of the spectrum. The LNG propulsion of Fure Viten provides a lower sound level in the engine control room for frequencies above 63 Hz.

The difference in A-weighted sound pressure level between propulsion modes in **the thruster rooms** is -2 to 3 dBA, the spectral differences are shown in Figure 23. These rooms are very noisy with measured sound levels of above 100 dBA and there was no perceptual difference during the measurements, it was just experienced as very loud. The results however show some variation. Aurora had a positive difference for most frequency bands, meaning that the electric propulsion was quieter than the hybrid. The reverse situation is seen for Tycho Brahe where the electric propulsion instead resulted in a louder noise situation. This could be due to different conditions during the measurements in hybrid and in electrical mode, e.g., an additional sound source or variations in load and/or rpm of rotating parts. For the road ferry Tellus, the electric propulsion mode gives a decrease in the sound pressure level in the thruster rooms in most frequency bands.

On the **bridge** there is almost no difference in A-weighted level between propulsion modes. Still some, mostly positive, differences can be seen in the measured sound levels in the low frequency bands in Figure 24. The sound environments in these rooms are perceptually dominated by ventilation, especially when no radio calls or alarms are active.

The difference in sound pressure level between propulsion modes in a staff **cabin** is shown in Figure 25. The results for the different ships should not be compared directly as the cabins are located in different places on the ships. There was a noisy rattling in the room during the measurement in hybrid mode on Aurora which most likely explains the large difference above 400 Hz. During the measurement in the cabin on Tycho Brahe it was noted that the sound was dominated by ventilation. We suspect that the negative differences between the propulsion cases in low frequencies are related to variations in the ventilation system.

Table 11. Difference in measured A-weighted equivalent level, for the vessels that have more than one propulsion mode.

Ship and room	Modes	Room	Difference in dBA
Elvy	Hybrid - Electric	Engine room stern	3
Elvy	Hybrid – Electric	Engine room middle	41
Elvy	Hybrid – Electric	Passenger deck side	6
Elvy	Hybrid – Electric	Passenger deck middle	15
Elvy	Hybrid – Electric	Middle zone	7
Elvy	Hybrid – Electric	Bridge	-2
Aurora	Hybrid – Electric	Generator room	30
Aurora	Hybrid – Electric	Engine control room	2
Aurora	Hybrid – Electric	Thruster room	3
Aurora	Hybrid – Electric	Bridges	2
Aurora	Hybrid – Electric	Cabin	4
Tycho Brahe	Hybrid – Electric	Generator room	29
Tycho Brahe	Hybrid – Electric	Engine control room	5
Tycho Brahe	Hybrid – Electric	Thruster room	-2
Tycho Brahe	Hybrid – Electric	Bridges	1
Tycho Brahe	Hybrid – Electric	Cabin	1
Tellus	Hybrid – Electric	Engine room	29
Tellus	Hybrid – Electric	Thruster rooms	0
Tellus	Hybrid – Electric	Bridge	0
Fure Viten	Diesel – LNG	Engine room	3
Fure Viten	Diesel – LNG	Engine control room	1
Fure Viten	Diesel – LNG	Bridge	1
Fure Viten	Diesel – LNG	Cabin	0

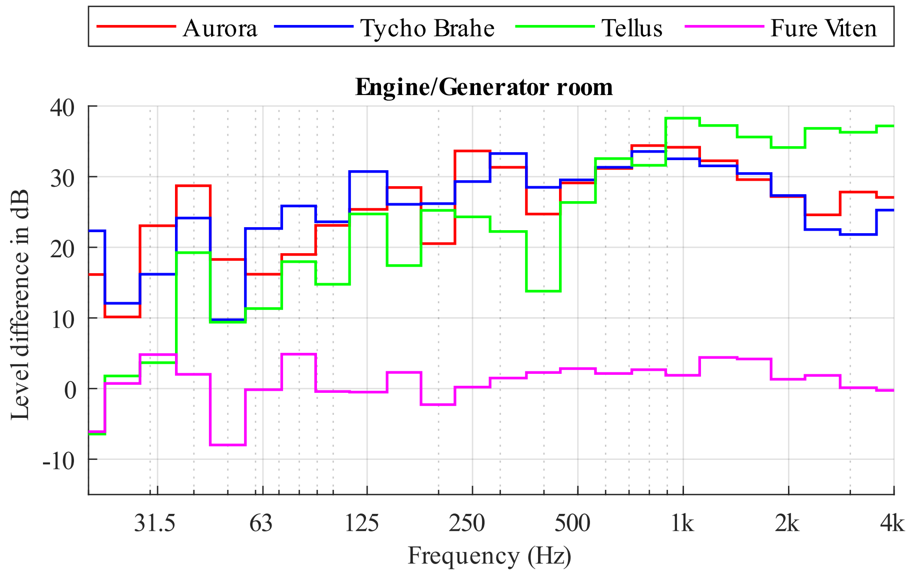


Figure 21. Difference of sound pressure level between the vessel's propulsion modes in the engine/generator room.

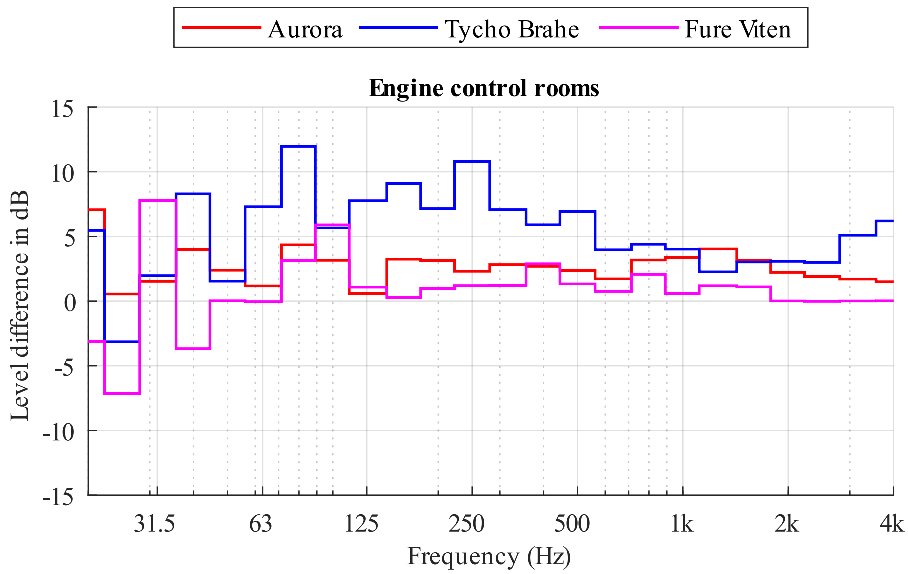


Figure 22. Difference of sound pressure level between the vessel's propulsion modes in the engine control room.

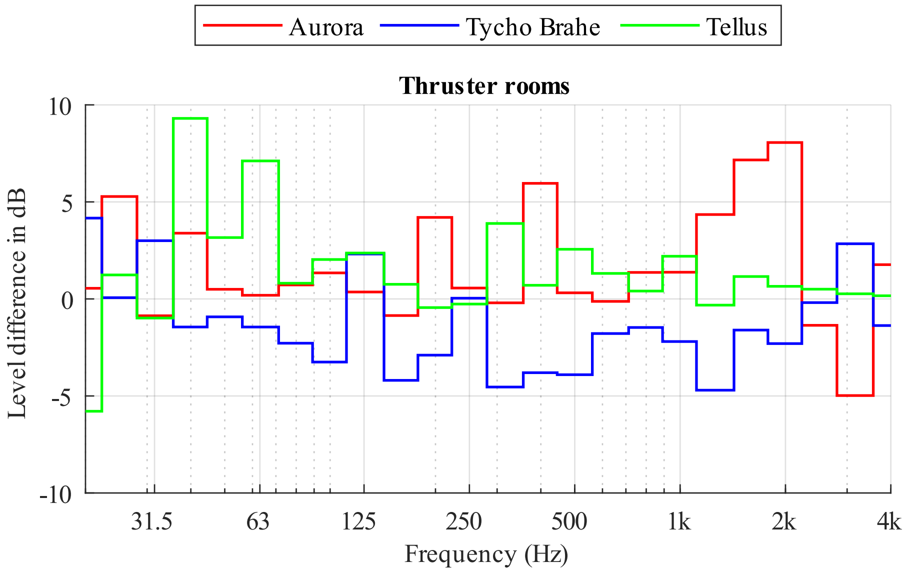


Figure 23. Difference of sound pressure level between the vessel's propulsion modes in the thruster room(s).

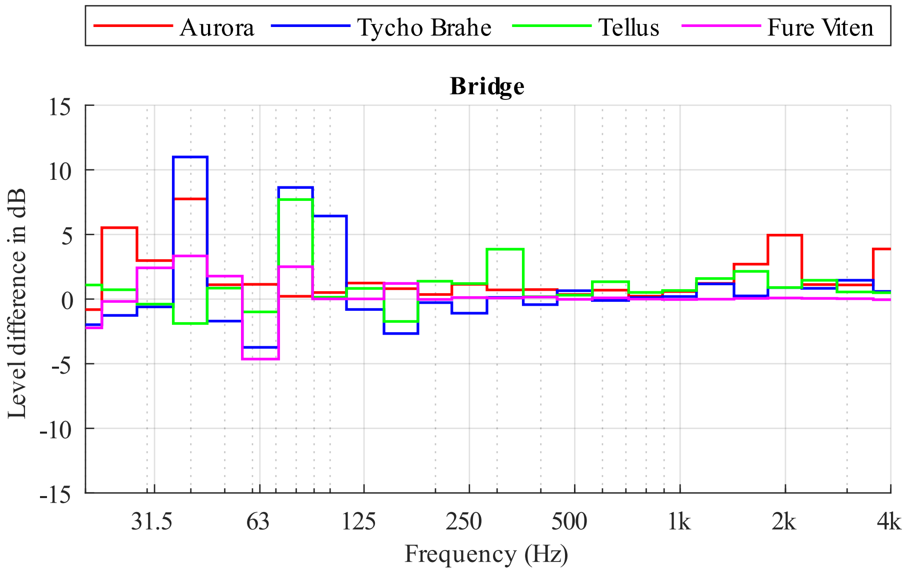


Figure 24. Difference of sound pressure level between the vessel's propulsion modes on the bridge(s).

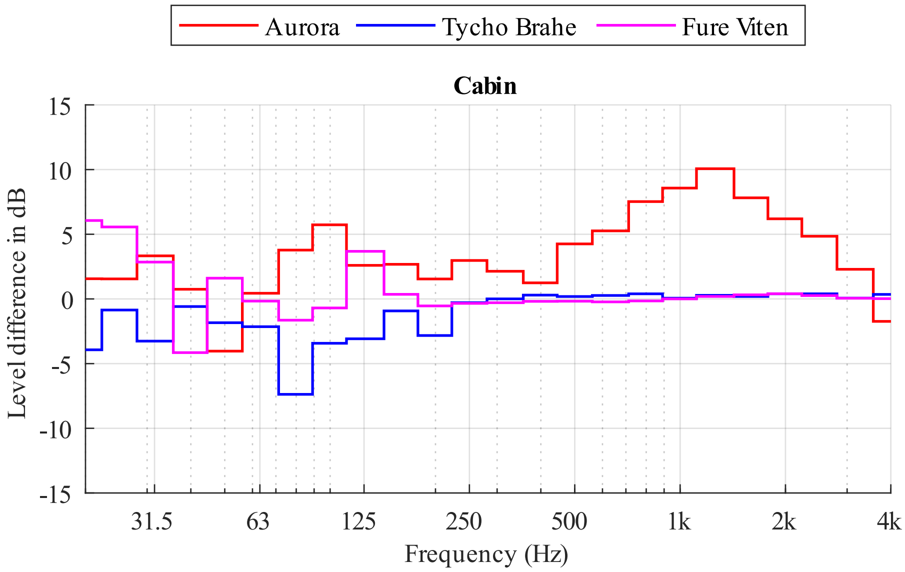


Figure 25. Difference of sound pressure level between the vessel's propulsion modes in a cabin.

Table 12 gives an overview of the differences of A-weighted total level comparing similar rooms in the sister vessels included in the project **in hybrid/diesel mode**. The differences can be studied further in the graphs in Figure 26–Figure 29, where the sistership-difference in sound pressure level in 1/3 octave frequency bands are shown.

The differences in A-weighted sound pressure level between sister vessels in hybrid mode are in general small with two exceptions: The thruster rooms on Aurora and Tycho Brahe, Figure 28, and the bridges on Neptunus and Tellus, Figure 29. As mentioned previously, Aurora was running with three thrusters compared to the four thrusters on Tycho Brahe which could be an explanation why she is significantly louder than Tycho Brahe in a large part of the spectrum. Several staff have commented on the radar on the bridge of Neptunus which could be an explanation to the difference between the road ferries.

There are spectral variations of the difference in the engine/generator rooms, Figure 26, which to some extent is evened out in the total A-weighted level. Aurora is slightly louder than Tycho Brahe in a large part of the spectrum except in the 80 Hz band. Tellus is also louder than Neptunus in most bands except at high frequencies.

The difference in sound pressure level in the engine control room of the ForSea ferries, Figure 27, shows a sharp shift. Aurora is clearly louder in the low frequencies (<160 Hz), whereas Tycho Brahe is louder in the mid and high frequency range.

Table 12. Difference in measured A-weighted equivalent level between similar vessels. The ForSea vessels are compared in hybrid mode, the Färjerederiet vessels in Hybrid/Diesel modes in 240 rpm.

Ship	Room	Difference in dBA
Aurora-Tycho Brahe	Generator room	2
Aurora-Tycho Brahe	Engine control room	-2
Aurora-Tycho Brahe	Thruster room	7
Aurora-Tycho Brahe	Bridges	1
Neptunus-Tellus	Engine room	1
Neptunus-Tellus	Thruster rooms	1
Neptunus-Tellus	Bridge	5

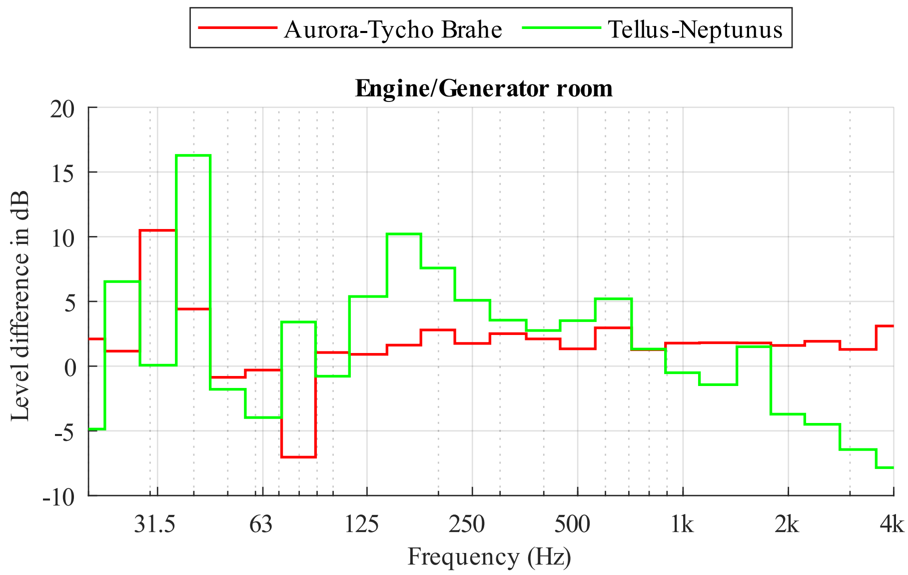


Figure 26. Difference of sound pressure level in the engine/generator room between sister vessels. The ForSea vessels are compared in hybrid mode, the Färjerederiet vessels in Hybrid/Diesel modes at 240 rpm.

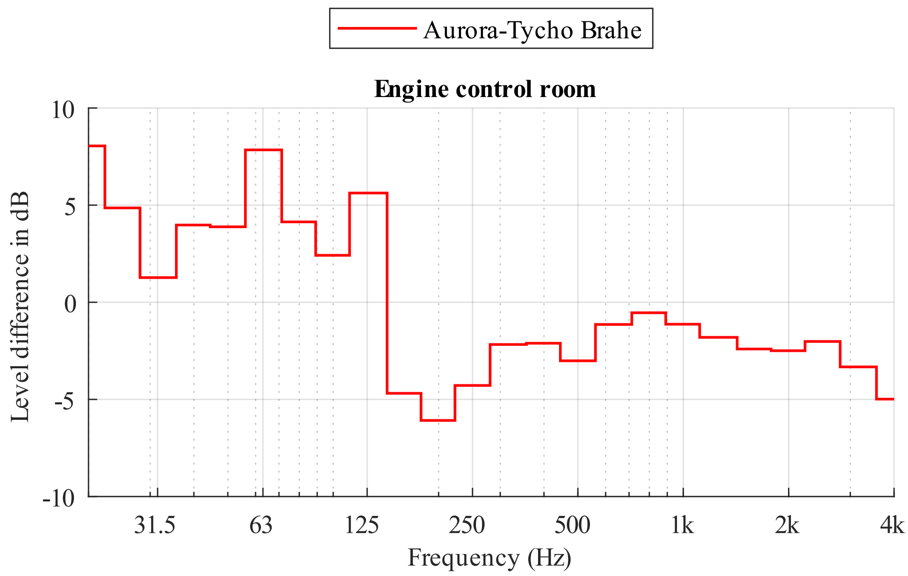


Figure 27. Difference of sound pressure level in the engine control room between sister vessels. The ForSea vessels are compared in hybrid mode.

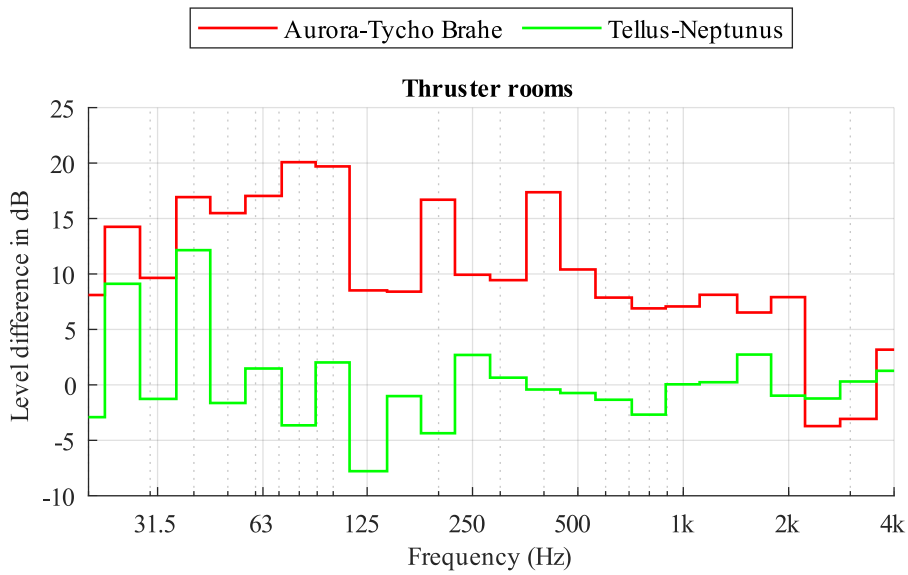


Figure 28. Difference of sound pressure level in the thruster rooms between sister vessels. The ForSea vessels are compared in hybrid mode, the Färjerederiet vessels in Hybrid/Diesel modes at 240 rpm.

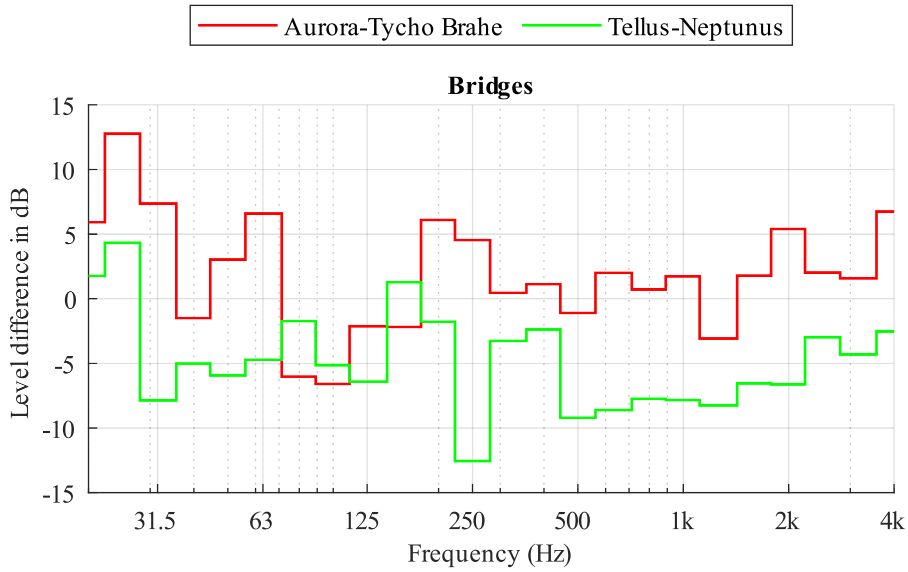


Figure 29. Difference of sound pressure level on the bridge(s) between sister vessels. The ForSea vessels are compared in hybrid mode, the Färjerederiet vessels in Hybrid/Diesel modes at 240 rpm.

4.3 Work and passenger environment

4.3.1 Work environment

The general and reoccurring results from the case studies are summarized in the following. This chapter focusses on aspects related to the propulsion, but other aspects of the working environment and how it could be improved were also mentioned during the interviews. Detailed results can be found in the Appendix under each case study.

The interviewees

There was a mix of gender, age, experience, and responsibilities onboard among the interviewees.

Perception of the work environment

The interviewees are in general satisfied with the overall working environment in all our case studies. Many refer to previous experiences of other older ships which were much noisier and worse from a work environment perspective.

The general opinion among our interviewees is that there is less noise with the modern propulsions. The difference depends on where you are in the ship. It is significantly much quieter with modern propulsion in the engine rooms and nearby spaces like the engine control room. It is also quieter outside on the deck during electric propulsion. Indoors, further away from the engines, like on the bridge, there is in general no prominent difference between propulsion types. It should be noted that also the LNG-propulsion mode onboard Fure Viten is experienced as significantly quieter than the diesel-mode, even though they use the same machinery.

Another effect of electrical propulsion is the more direct/faster response between the bridge controls and what happens with the ship in the water and the lack of feeling the rpm changes of the motors. There are also new noise sources onboard connected with the charging of batteries, inverters and electrical motors.

Typical in acoustics, when one sound source decreases, others start to become distinguishable. This could be a reason why we had several comments about ventilation noise, especially in the cabins and on the bridge.

Noteworthy, even if it is not directly related to the propulsion, is that several interviewees commented about being disturbed by alarms and people moving around when they are off duty and should rest and recover.

Vibrations are in general seen as a natural part of being onboard a ship. At the same time, mitigations like better working shoes and vibration isolating carpets are suggested. Most vibrations occur during mooring, when braking heavily and from waves and poor weather conditions.

Work environment risks

Commented work environment risks were not specifically linked to noise and vibrations but rather to falls, crushing, vehicle stowage, chemicals, freezing, ship movements in bad weather, risks with ropes and winches.

Suggestions for improvements

There were a number of different improvements mentioned in the interviews. The ones related to sound and vibrations from the ship itself were:

- More quiet ventilation.
- Mitigating vibrations with damping mats and better shoes.

- Improve unnecessarily noisy or loud equipment like radars, alarms, radio, doors slamming.

- Decrease disturbing sound transmission to cabins and other rooms for rest or where there is a need to concentrate.

4.3.2 Passenger environment

The general results from the case studies which included passenger's experience of noise and vibrations onboard are summarized in the following. Detailed results can be found in the Appendix under each case study. In total 556 persons answered the questionnaire, 355 in electric and 201 in diesel or hybrid propulsion mode.

The passengers were, in general, not disturbed by the ferries' noise and vibrations, regardless of propulsion mode. The majority of answers are found under "Very low/Not disturbing" or "Quite low/Slightly disturbing". We suspect the respondents have focused on the word "*disturbing*" as more passengers report "Very low/Not disturbing" in electric propulsion, while more passengers report "Quite low/Slightly disturbing" in hybrid mode.

Figure 30 provides an overview of the results from the question "How do you perceive the noise from the ferry itself?". The results show that the passengers' experience of noise on board differs between electric and hybrid/diesel propulsion in two out of three cases. More people experience the noise from the ferry as "Very low/Not disturbing" in electric mode compared with diesel/hybrid mode. The exception is the road ferries trafficking Gullmarn, where the difference is very small between propulsion types. This might be explained by the situation; the passengers were mostly inside their own vehicles during the passage which isolates some of the noise from the ferry.

The result from the question "How do you perceive the vibrations from the ferry itself?" were not as clear as for the noise but show similar tendencies.

The question about the comfort, "How satisfied are you overall with the onboard comfort in terms of noise and vibrations on this journey?" indicates differences between electric and hybrid propulsion but it is difficult to analyze in detail. It may have targeted a wide range of impressions, including speaker calls, other passengers, and music.

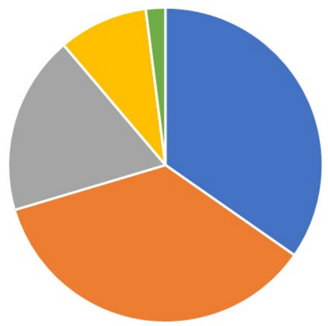
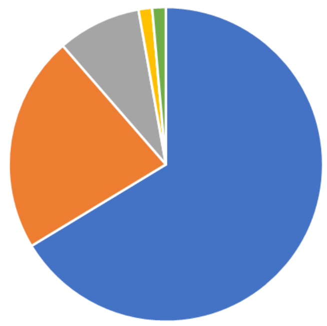
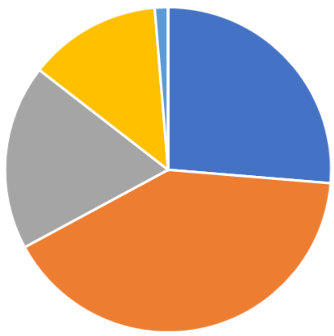
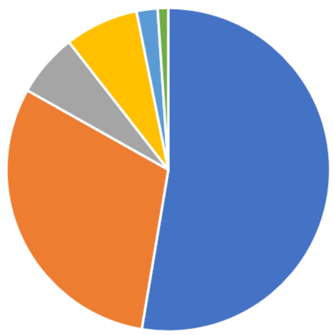
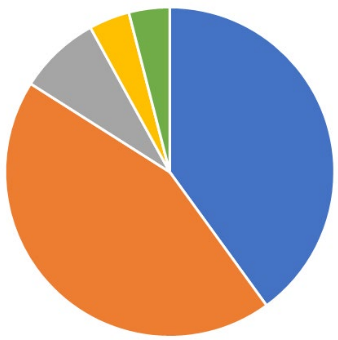
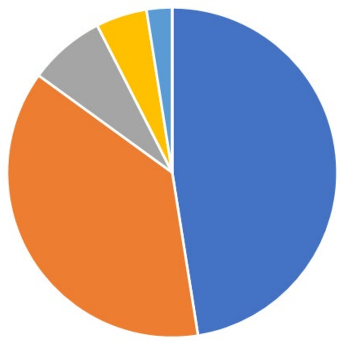
How do you experience the noise from the ferry itself?		
	Hybrid/Diesel propulsion	**Electric propulsion**
Styrsö-bolaget Elvy (hybrid and electric)		
ForSea Hamlet (diesel) & Aurora (electric and hybrid)		
Färje-rederiet Neptunus (diesel) & Tellus (electric mode)		

Figure 30: Results from the passenger survey from the three case studies and the answer to the question "How do you perceive the noise from the ferry itself?". The available answers were:
Very low/Not disturbing (dark blue)
Quite low/Slightly disturbing (dark orange)
Neither or (grey)
Quite high/Disturbing (yellow)
Very High/Very disturbing (light blue)
Have no opinion (green)

5 Discussion / Analysis

5.1 General

The selection of radiated noise measurement strategy depends on several factors. In this project, we performed two types of measurements on ferries. On-site measurement in route were performed where environmental noise levels permitted. Where they did not, the vessel was taken out of service and taken to a quiet location for dedicated measurements. Vessels in spot trade are not suitable for dedicated measurements due to the short planning horizons with this type of operation. Instead, we designed a bespoke autonomous measurement station. This worked as intended but due to few sensors and poor control of transmission losses, its accuracy was lower than the dedicated measurements. A more accurate way of measuring radiated noise from ships in spot traffic is needed.

The on-site measurements could in two cases be performed under normal routine operation of the ships, with some small adjustments to the typical sailing routes. The measurements in Gullmarn offered very good acoustic data quality, since the area was mostly devoid of other ships. This allowed many repeated passages of the ship under test, enabling the investigation of multiple operation conditions and still retaining a reasonable number of passages per condition. The measurements in Öresund had more ships in the area, which reduced the number of acceptable passages and thus the number of conditions that could feasibly be measured. Whilst Elvy was measured outside her normal harbor-bound operation in an area more distanced from the large shipping vessels, there was still a strong presence of recreational boating in the measurement area. Even though this dedicated measurement allowed postponing passages until there were no ships in the area, often recreational boats without AIS-transmitters entered the measurement area during ongoing measurements. This meant that the number of acceptable passages during a measurement day was similar as the measurements in Öresund. This highlights two things: the importance of measurement site, and that it is very doable to measure ferry-style traffic in regular operations.

The main goal here was to perform comparative measurements, comparing the same ship measured in different operating conditions. The on-site measurements were done over short time periods, such that the environmental conditions that influence sound propagation were very stable between the operating conditions. The ship under test also sailed in a pre-determined measurement track, following the track with a high precision. The ship operation was also very similar during the different passages in a single condition. This is in contrast with the opportunistic measurements performed for the Furetank vessels. Here, each measurement was performed on different days with different weather conditions. Additionally, the schedules of the ships were such that there are very few measurements from each ship, and with varying operating conditions with respect to cargo load etc. Moreover, since these measurements were performed in a highly trafficked fairway, the ship could often not follow the planned measurement track. All these factors combined give a high uncertainty in both the propagation loss and the actual source characteristics of the ship.

The Silent@Sea project has had to perform two of its case study measurements at night. In Öresund and Gullmarn, there were so many ships operating on the same route during the day that we judged that radiated noise measurements would probably pick up noise from more than one vessel. Such measurements would have been useless to the project. Radiated noise measurements were performed within 100-200 m range from the passing ships. In Öresund, the measurement boat was triple anchored, and it would have taken some time to move it if the need had arisen. We have been able to perform these measurements without major incidents, although in Gullmarn there was an incident when a trawler caught one of the anchors of the raft. Luckily the anchor line broke and the raft could be rescued. Although we have devoted a lot of effort to risk mitigation, ambitious researchers working with a limited budget are likely to take some risks on site to get the desired results. We will consider how to improve our processes to reduce risks during future measurements in route.

Detailed planning and communication with ship captains was of paramount importance to the accident-free and successful performance of the field trials. It was especially important to speak directly to the captains, who are responsible for the safety of the ship, its crew and passengers, and who make the operative decisions at sea. For example, we initially proposed a more northerly measurement track for ForSea, which our main ForSea contacts did not protest, but the ship captains decided that it was too close to other traffic and suggested the southerly track that was employed.

Silent@Sea made measurements of sister vessels because we wanted to attribute noise differences to the propulsion mode. However, in one case study there were differences between sister vessels that may have had an effect on the noise. In another case study, we were only able to measure the noise of one vessel. The focus in these cases was thus shifted to investigate the impact of hybrid propulsion modes via diesel engine electric generators as compared to fully electric battery powered propulsion – essentially measuring the noise radiation from diesel engines (and supporting systems) separated from the rest of the propulsion systems. In the Färjerederiet case, the vessels Neptunus and Tellus however are true sisters except that the propulsion is different.

For Furetank, we have compared newer and older vessels of similar dimensions and capacity. The newer vessels appeared to be quieter, but no explanation was provided. Showing continuous improvement in environmental performance is important to many ship operators, and it would be relevant to perform similar studies on other vessels.

Only one case study on LNG vessels was performed. More studies are needed in order to draw general conclusions. It would also be interesting to investigate the effects of emerging fuels such as methane and ammonia on noise levels, in particular onboard.

Silent@Sea measured ships at cruise speed only, except the Färjerederiet vessels which were measured also at a lower speed. Cruise speed measurements are relevant as the ship typically operates at cruise speed, but measurements at lower speeds and during manoeuvres are relevant to capture the full noise impact of a ship and may be particularly important to the impact of airborne noise on nearby residents. At lower speeds, the underwater noise benefits of electrical propulsion may be greater, if the propeller does not cavitate.

Noise mitigation was not addressed in the present study but more studies on methods of noise mitigation are needed. If noise mitigation is to happen, policies and incentives that motivate them also need to be implemented. In general, ship noise needs to receive more attention, and not least its impact on health and marine life. Finally, noise should be included in the green shipping concept, so that synergies and goal conflicts can be identified.

5.2 Radiated noise

5.2.1 Airborne noise

Results from comparisons between hybrid and electric propulsion modes show that the main difference is found around the fundamental frequency of the engine, which is to be expected. The main source of noise radiation is likely to be the engine exhaust funnel, which is often one of the highest points of a ship. A high source of low frequency noise radiating over an acoustically hard surface like water comprises almost ideal sound propagation conditions and it is safe to say the low frequency noise from ships is likely to be heard far away. Considering the directionality exhibited by Tellus when measuring the difference between funnels facing away from or towards the microphones, ships with directional characteristics of the funnels may exhibit even more efficient noise radiation such that the assumption of point source like spherical radiation is erroneous and could underestimate the sound propagation properties and thus the noise exposure levels at nearby dwellings. By adopting electric propulsion, the low frequency noise can be substantially reduced, and the high placed, potentially directional source is essentially removed.

Radiated noise measurements are weather sensitive, and beneficial and stable weather conditions are crucial to obtain comparable radiated noise data. The most difficult weather condition to fulfil was to have a wind speed below 5 m/s, specifically considering that even though such low wind speeds may occur at sea, it needed to coincide with all other aspects of the measurement planning.

The method using a floating platform for microphone placement turned out to be successful, although some challenges were presented when attempting to anchor the raft in Öresund in conditions of high underwater currents and powerful wind gusts. As predicted by the weather forecast both the current and the wind luckily died down in time for the measurements.

5.2.2 Underwater noise

The overall results are that the onboard diesel engines for electricity generation have a minor impact on the underwater radiated noise. Only for the smallest vessel studied, Elvy, did operation of the diesel engine have a measurable impact on the overall radiation. This indicates that a properly mounted diesel engine, operating as an electric generator, does not contribute strongly to the underwater noise radiation.

Diesel engines that ultimately produce electricity are mostly operated at the ideal rate to have optimal fuel efficiency. In contrast, when used in conventional propulsion systems, these engines must operate at rates determined by the momentary propulsion power needs for the ship. This potentially introduces stronger vibrations of the ship hull if the engine operates at rates lower than the compliant suspension is designed for, thereby increasing the radiated noise. The suspension could potentially be improved for hybrid propulsion as well since the diesel engine no longer requires a fixed connection to the propulsion system. This would allow the diesel engine and generator to be suspended as a whole with a softer suspension than could otherwise be realized. Furthermore, the propulsion shaft is necessarily connected with quite a high stiffness to the ship hull, and hybrid propulsion would fully decouple the diesel engine from any propulsion shaft. Electrical motors are to their nature less violent, thus creating less vibrational energy that can excite the hull.

Tellus and Neptunus offers the clearest comparison between a ship with hybrid propulsion and its conventional counterpart. Tellus originally had the same diesel engine propulsion system as Neptunus, but was retrofitted with electric motors, generators, and batteries. According to our measurements, Tellus radiates less underwater noise than Neptunus, with up to 10 dB in some 1/3 octave bands. This is an indication that retrofitting ships with modern hybrid propulsion is a potential way to reduce their noise radiation. To fully investigate this, measurements should be done on the same vessel just before and after such a retrofit.

5.2.3 Noise source identification

Noise sources were identified mainly using technical information about engines, thrusters, propellers and their speeds. The vibration data that we recorded contained a great many tonal components that often could not be related to the source on which a certain accelerometer was placed. It is possible that this would have been remedied with better accelerometers and more careful attention to placement and mounting.

Source identification was largely successful; we managed to identify the sources of most tonal components in radiated noise data. However, this method does not permit source identification of broadband noise. A better method would be desirable, ideally one that processes onboard vibrations and radiated noise data together.

5.3 Onboard noise

The ship operators made a lot of effort to make repeated passages at the same conditions, which resulted in good repeatability radiated noise data. Onboard noise is more affected by events close to the receiver, such as machinery or pumps that start running, heating and ventilation as well as crew and passengers moving on the ship and making noise. These events are difficult, if not impossible, to control. The noise data presented here are recorded when the researcher subjectively judged that the noise at the recording site was steady. However, it is not possible to judge the state of nearby machinery and mechanical equipment, and additional noise sources and variations in their operation may have influenced the measurements. This is also the reason we could only measure the sound level in passenger rooms on Elvy and not on the ForSea ferries, as they were measured during their normal traffic and the variation of passenger sounds would compromise the propulsion mode comparison.

The absolute values of our measurements, found in the appendix under each case study, should be considered as indicative due to the difficulties to follow a measurements standard. The general trends in the results can however be considered and e.g. compared to the recently published overview on measured onboard ship noise by Bocanegra et al., 2023. The A-weighted results from our measurements in the

- engine/generator and engine control rooms in hybrid/diesel/LNG mode are in the louder range of the category "Work" for commercial vessels

- engine/generator and engine control rooms in electric mode are in the quieter range of the category "Work" for commercial vessels

- bridges are in the quieter range of the category "Navigation" for commercial vessels

- cabins are in the quieter range of the results of the category "Accommodation"

The trends in the spectra of our measurements can also be compared with by Bocanegra et al., 2023. In general, we see similar tendencies with decreasing levels with increasing frequency even though our results in the "Work" category are varying and depend on propulsion mode. Notable in this comparison is the sound pressure level in the cabin and on the bridge of Fure Viten, where we do not see the expected decay above 300 Hz. One possible reason could be the ventilation noise or alarms which was a topic that came up during the interviews with the crew.

5.4 Work and passenger environment

The work environment study was based on semi-structured interviews with crew and yielded mainly positive responses about electrical or LNG propulsion in comparison to conventional propulsion and older vessels. Other problems, both noise related and others, came up during the interviews and many suggestions of improvements were noted and can be found in the appendices. The relatively limited number of participants is one of the limitations to this part of the project.

The results from the passenger questionnaire indicate that, even though passengers were not disturbed by the ferry's noise and vibrations, regardless of propulsion mode, they can still perceive a difference between the modes. One limitation to this part of the study is the lack of an analysis to confirm that the difference is statistically significant.

It is tempting to compare the work and passenger environment results related to different propulsion modes, to the measured difference in sound pressure level. The results align well in some cases, i.e., on Elvy where more passengers are very satisfied and not disturbed by noise and vibrations during the electric propulsion compared with hybrid mode, and the measured difference is 6-15 dBA. In others, the connection is less obvious, i.e., on Fure Viten there was comments about LNG propulsion being quieter, especially in the engine room and control room. However, the measured difference was only 1-3 dBA. There could be a number of the reasons for the deviations, the foremost perhaps being that the measurement were conducted during steady state travel in contrast to the perception of noise and vibrations that encompass all kinds of conditions.

6 Conclusions

All the measurements in this project yielded relatively undisturbed results, except when wind disturbed airborne noise measurements. This together with the fact that data was successfully collected on ships of different operating conditions indicates that our measurement strategy was successful.

We have shown that simultaneous measurement across several domains is cost-effective and simplifies identification of noise sources. Onboard noise measurements are far easier to execute than radiated noise measurements because they are relatively insensitive to external disturbance and moreover the ship does not need to follow a prescribed track. They are however more sensitive to the operating conditions of the ship, where numerous smaller machines near the measurement sensors can have a much larger impact on the measurement results.

We have also shown that ship noise radiation can be measured in normal operation, even in busy shipping lanes, when working in close cooperation with ship operators. The success of Silent@Sea depended on establishing good relations with the ship operators. Detailed planning together with the ship operators and frequent communication between researchers and operators were crucial to the success of the project. This hinged on the interest of the ship operators in the topic of Silent@Sea and the researchers' respect for their business and its conditions.

The **working and passenger environment** is improved by a shift to modern propulsion. This is coupled to decreased onboard noise levels**. Onboard noise reductions** at electrical propulsion are associated with the lack of diesel engine noise. Onboard noise reductions were also observed for the LNG vessel that was studied. This was attributed to different operation characteristics of the engine when running on LNG e.g., different engine speed.

Radiated airborne noise is improved by a shift to electrical propulsion. However, there are still low frequency tones, which may travel far and potentially disturb nearby residents. Our results for LNG-powered vessels are weak because of wind disturbance.

Small or no changes in **underwater noise** levels were observed between electrical/LNG propulsion and their more conventional counterparts. For diesel-electric and hybrid vessels, engines/diesel generators are a minor contributor to underwater noise at cruise speed. Propeller noise is important but other sources including gears and noise typical of electrical motors contribute. A change of fuel on a ship may influence underwater noise levels through different operation characteristics of the engine(s). However, such changes are likely to be small, and could not be detected in the studies performed here.

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Appendices

A Passenger questionnaire

The Swedish language form used in the passenger survey onboard the ForSea ferries is provided in the following. Similar forms were used in all passenger surveys.

Bästa resenär!

IVL Svenska Miljöinstitutet driver ett forskningsprojekt (*Silent@Sea*) kring buller och vibrationer vid övergång till alternativa energislag på fartyg.

Idag undersöker därför IVL hur ForSeas/Auroras resenärer upplever resan avseende buller och vibrationer och vi vill att du svarar på några påståenden. Enkäten kommer att samlas in under resans gång!

Om du tänker på din upplevelse av resan som du gör just nu - Ringa in ditt svar:

Hur upplever du bullernivån från själva färjan?

Mycket låg/ Inte störande	Ganska låg/ Lite störande	Varken eller	Ganska hög/ Störande	Mycket hög/ Väldigt störande	Vet inte
1	2	3	4	5	0

Hur upplever du vibrationerna från själva färjan?

Mycket små/ Inte störande	Ganska små/ Lite störande	Varken eller	Ganska stora/ Störande	Mycket stora/ Väldigt störande	Vet inte
1	2	3	4	5	0

Hur nöjd är totalt sett med komforten ombord avseende buller och vibrationer på den här resan?

Mycket missnöjd	Ganska missnöjd	Varken eller	Ganska nöjd	Mycket nöjd	Vet inte
1	2	3	4	5	0

Har du några övriga kommentarer eller synpunkter på resan avseende buller och vibrationer som du vill framföra?

Vänligen vänd på pappret

Några frågor om dig

Hur ofta reser du med ForSea?

- ☐ Mer sällan
- ☐ 1–3 dagar per månad
- ☐ En dag per vecka
- ☐ 2–4 dagar per vecka
- ☐ 5–7 dagar per vecka
- ☐ Vet inte

Vad är det huvudsakliga syftet med den här resan?

- ☐ Till/från arbete
- ☐ Till/från skola/studier
- ☐ Resa i tjänsten
- ☐ Fritidsresa
- ☐ Turist
- ☐ Inget av alternativen

- ☐ **Ålder**? _______ år

Är du?

- ☐ Kvinna
- ☐ Man
- ☐ Annat
- ☐ Vill ej uppge

Tack för din medverkan!

B ForSea – hybrid vs electrical propulsion on RoPax ferries

B.1 Introduction

The ForSea case study was performed in 2022 and 2023. An initial visit to the ships was performed in March 2022. Crew interviews were performed 24-25 March 2022, and the passenger surveys 1 March 2023. The radiated noise measurements (Table 13) were performed 20-21 April 2023 together with onboard noise and vibration measurements. Additional onboard measurements were made on 10 May 2023.

Table 13. ForSea radiated noise measurement log.

Time	Vessel	Propulsion	Distance to hydrophones	Distance to microphones	Included in analysis
23:16	Aurora	Electric	153 m	85 m	Yes
00:16	Aurora	Electric	171 m	105 m	Yes
00:56	Tycho Brahe	Hybrid	481 m	415 m	No
01:27	Aurora	Electric	173 m	106 m	Yes
02:06	Tycho Brahe	Hybrid	158 m	91 m	No
02:45	Aurora	Hybrid	179 m	113 m	Yes
03:16	Tycho Brahe	Hybrid	154 m	86 m	Yes
03:56	Aurora	Hybrid	174 m	108 m	Yes
04:36	Tycho Brahe	Hybrid	156 m	88 m	Yes
05:05	Aurora	Hybrid	165 m	99 m	Yes
05:38	Tycho Brahe	Hybrid	819 m	784 m	No
06:06	Aurora	Electric	175 m	109 m	Yes
06:38	Tycho Brahe	Hybrid	156 m	88 m	Yes
07:10	Aurora	Hybrid	180 m	114 m	Yes
07:42	Tycho Brahe	Electric	138 m	71 m	Yes

The positions of the measurement track and noise sensors are presented in Table 14 below.

Table 14. Positions of measurement track and sensors for the ForSea radiated noise measurements.

Position	Coordinates
Measurement track, start	56° 2.1224' N 12° 40.9992' E
Measurement track, end	56° 1.8031' N 12° 40.9087' E
SilentRaft	56° 1.956' N 12° 41.0300' E
Hydrophones	56° 1.9501' N 12° 41.0965' E

Figure 31 presents photos from the ForSea studies.

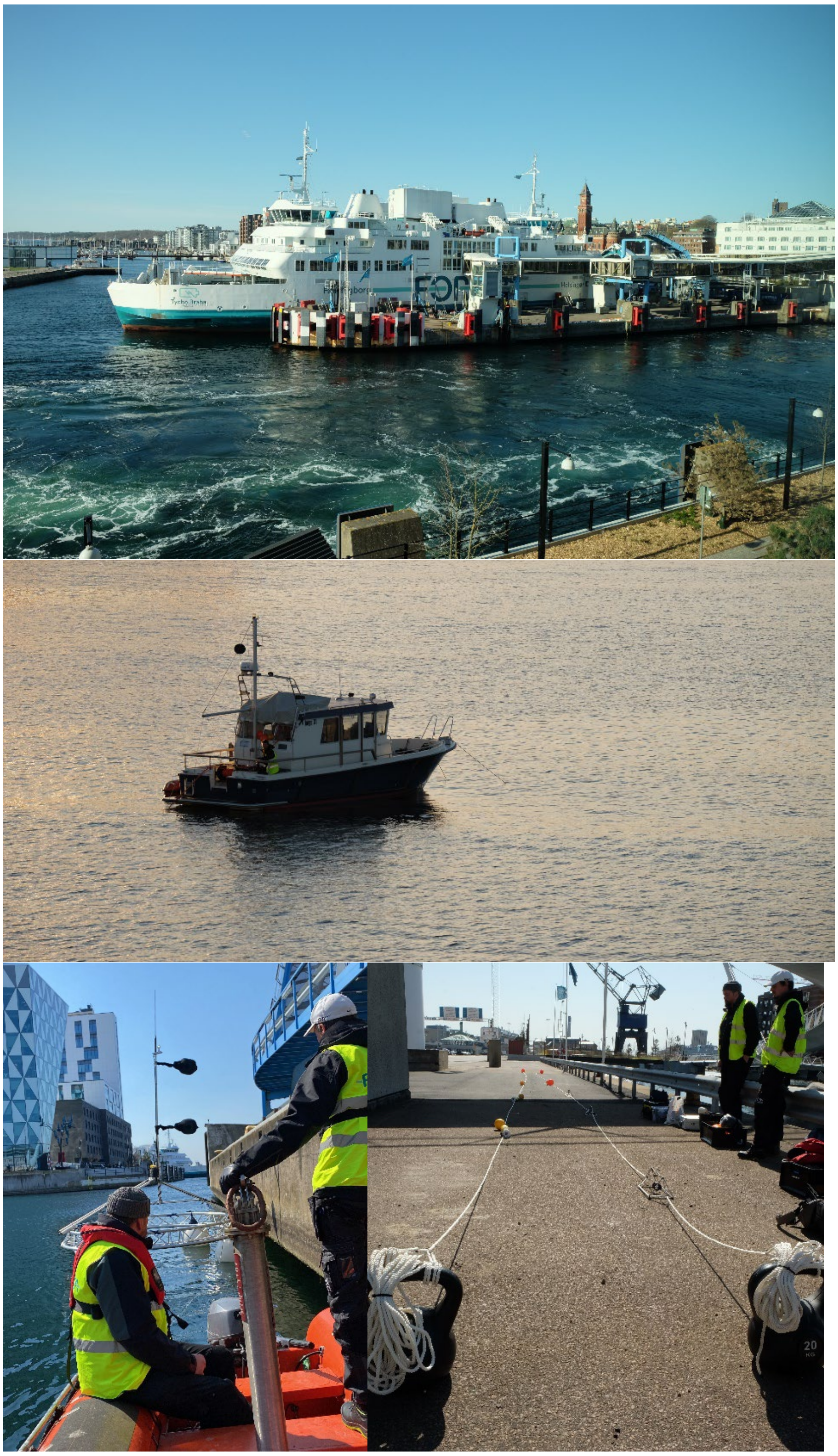

Figure 31. Photos from the ForSea radiated noise measurements: Aurora at quay (top), the work boat (middle), towing the SilentRaft to the measurement site (bottom left) and the hydrophone lines used (bottom right).

B.2 Radiated noise

B.2.1 Airborne noise

For ForSea the ferries Aurora and Tycho Brahe were measured in fully electric or hybrid diesel electric modes, although due to some technical issues with Tycho Brahe only one passage was recorded under fully electric propulsion. Figure 32 shows the average of passages in electric propulsion mode for Aurora in blue and for hybrid propulsion mode in red. As can be seen, the difference between propulsion modes was not very significant for Aurora. Figure 33 show the same comparison for Tycho Brahe and it should be noted there was only one passage by performed in electric propulsion mode, but if that single passage could be considered representative, the difference is much more pronounced for Tycho Brahe than for Aurora. Still there can be seen a clear difference of about 6 dB in the 40 Hz band for Aurora, which corresponds well to the slower revolution speed of the larger engines compared to Elvy. For Tycho Brahe the difference between propulsion modes in the same frequency band is about 12 dB.

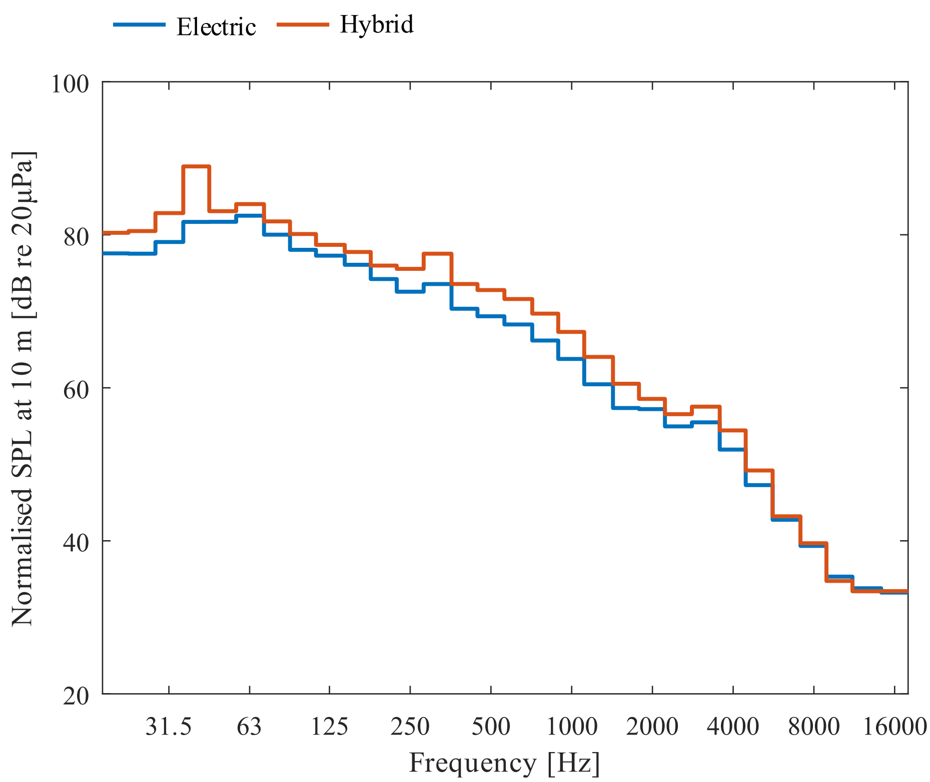

Figure 32. 1/3 octave band spectra of airborne noise from Aurora under electric and hybrid propulsion modes.

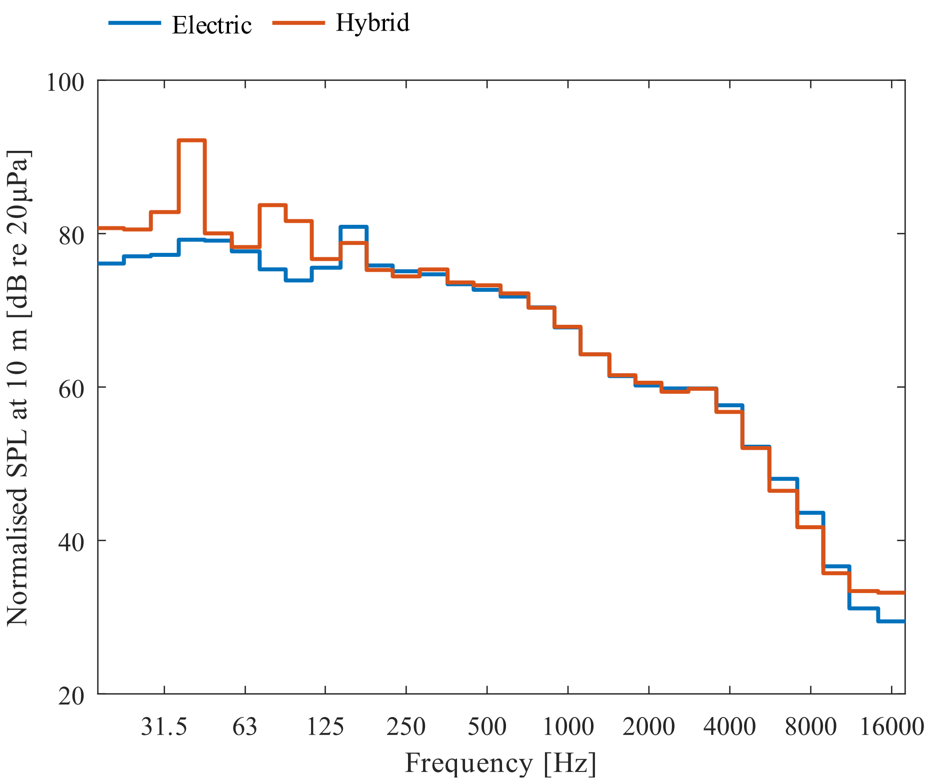

Figure 33. 1/3 octave band spectra of airborne noise from Tycho Brahe under electric and hybrid propulsion modes. Note that Tycho Brahe only performed a single pass under electric propulsion mode.

B.2.2 Underwater noise

The underwater noise measured from Aurora running with the diesel generator enabled "hybrid mode" and disabled "electric mode" is shown in Figure 34. The average results in electric and hybrid are both within the range of results from the other propulsion mode. This means that the noise radiation is not measurably different. In most of the frequency range the overall spread of the measured noise is low, around 4 dB, indicating a very accurate measurement setup with good repeatability between the different passages. However, in the 500 Hz band and those next to it, the range of measured results are larger. When investigating this effect in detail, there is a trend that passages performed later in the morning have a higher level than those earlier during the night. This effect is likely environmental, related to the sound propagation in the water.

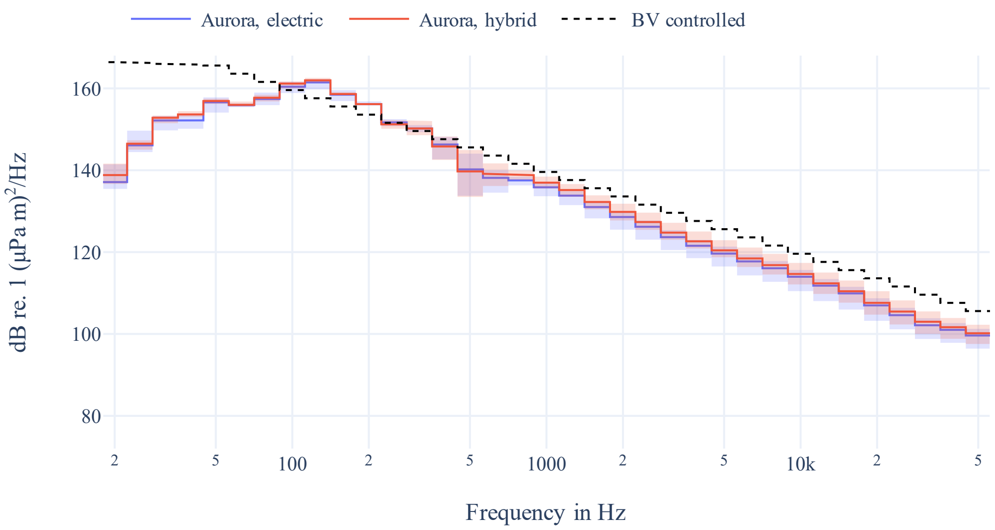

Figure 34. Underwater radiated nosie from Aurora in electric and hybrid mode. The shading indicate the largest spread of noise levels between the measured passages.

Comparing Aurora with her sister vessel, Tycho Brahe, Figure 35 shows that Tycho Brahe is quieter than Aurora, even though both ships have the same physical dimensions and are sailing at the same speed. Aurora was operating with three thrusters in the water during the measurements, instead of four which is the designed specification for both ships. This means that Aurora used more power for each thruster, thereby increasing the loading of the propellers. This increased loading is one likely explanation for the increased noise from Aurora since the noise generation is not linearly related to the propulsion power.

Figure 35. Underwater radiated noise from sister vessels Aurora and Tycho Brahe. The shading indicate the largest spread of noise levels between measured passages.

The results for Tycho Brahe in different modes are shown in Figure 36. Similar to Aurora, there is no measurable difference in fully electric or with diesel generators active. The exception is in the 50 Hz band, where the noise radiation is increased by 10 dB. However, the fully electric condition was only measured during a single passage, so that frequency band could be affected by other unknown noise sources.

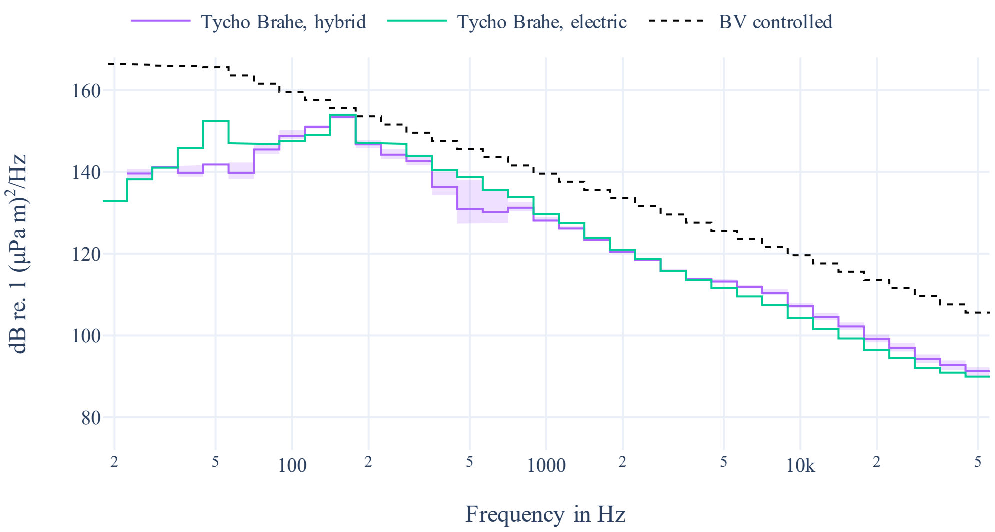

Figure 36. Underwater radiated noise from Tycho Brahe. The shading indicate the largest spread of noise levels between measured passages. Note that only a single passage was performed in fully electric mode.

B.2.3 Noise source identification

The received noise level is shown with high frequency resolution for Aurora and Tycho Brahe in Figure 37 and Figure 38 respectively. These figures show the results in air and in water in the two rows, and the electric and hybrid cases as two lines in each axis. The identified tones are also shown in these figures, by coloring each peak with the corresponding color.

Comparing the results for Aurora in fully electric mode and hybrid mode, there are distinctly visible tones from the diesel generator at 12.5 Hz both in air and water, and a strong tone at 37.5 Hz in air. The generator operates at 750 RPM, which corresponds to a frequency of 12.5 Hz. The strong airborne third-order harmonic is also expected since the diesel engine is a six-cylinder four-stroke engine, which has 3 ignitions per revolution. Looking at the results in the water, there is a steady increase in the broadband cavitation noise from around 20 Hz and upwards to 100 Hz, similarly to in Figure 34.

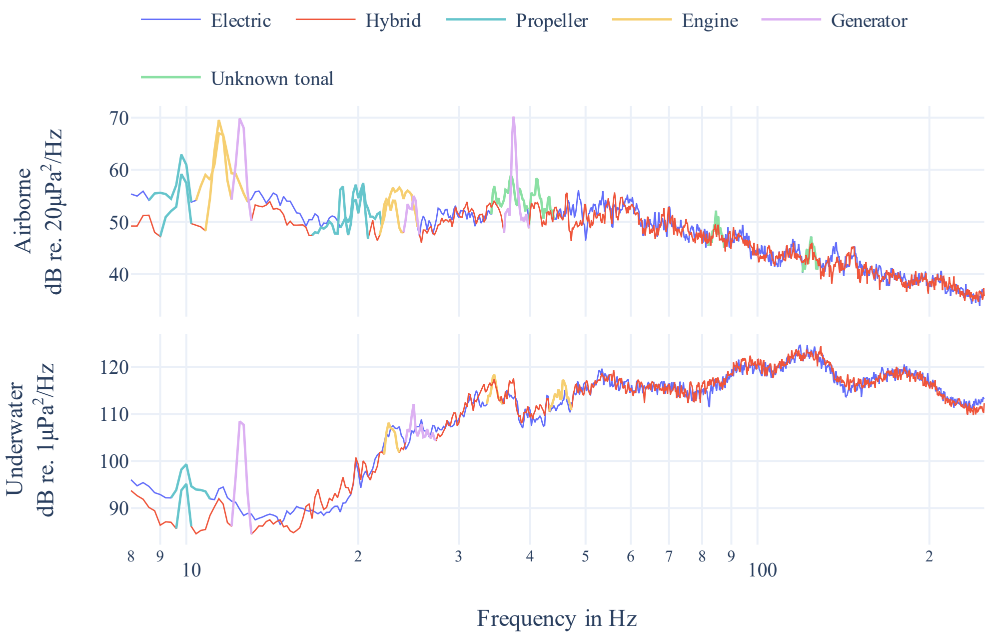

Figure 37. Identified tones for Aurora.

The results for Tycho Brahe also include the strong airborne tone at the diesel ignition frequency at 37.5 Hz. At the lower end of the analyzed range, the main component is from the engine, and no clear tones from the propeller is visible. In the higher frequency range, there are plenty of tones, many of which do not match any of the known sources. Recall that the electric mode was only measured in a single passage, so the many unidentified underwater tones between 35 Hz and 80 Hz might be caused by another source in the area.

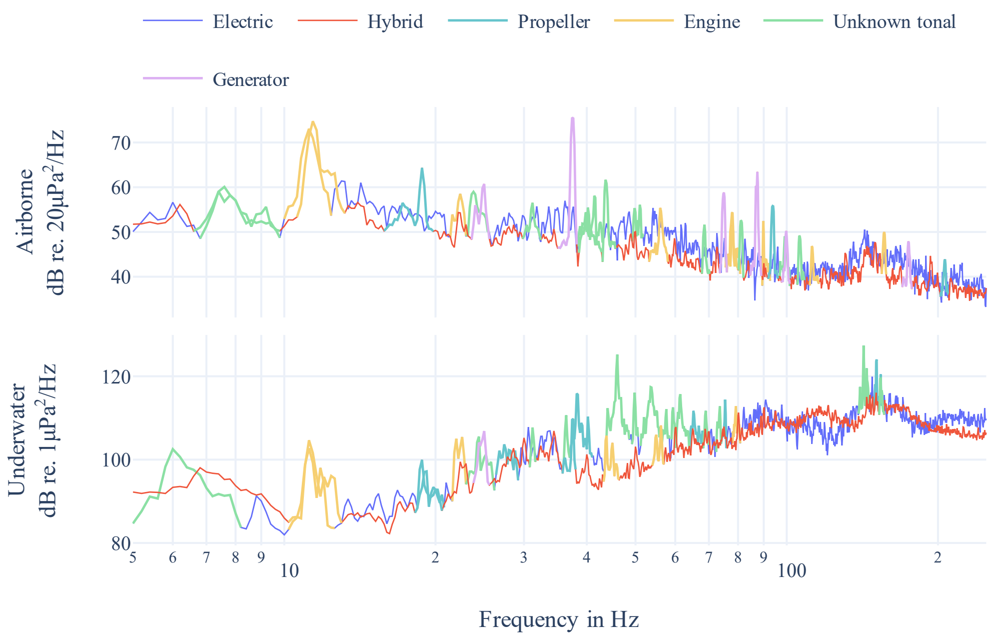

Figure 38. Identified tones for Tycho Brahe.

Converting these tones into a total power metric and comparing to the total power in this range yields the power distribution chart shown in Figure 39. This clearly shows the strong contribution of the cavitation in water, and the effect of the diesel generator for the airborne noise.

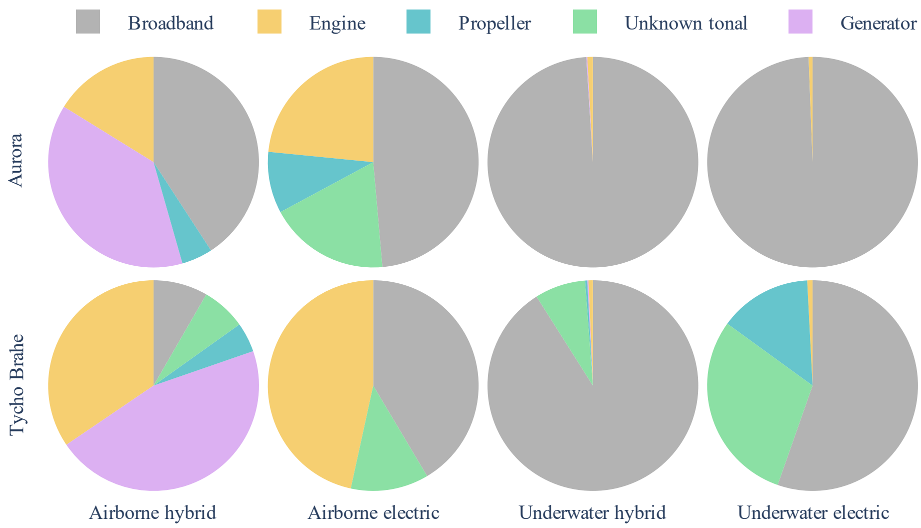

Figure 39. Noise power distribution for Forsea ships

B.3 Onboard noise

Onboard noise was measured on Aurora and Tycho Brahe during daytime on the 10th of May 2023, a few weeks after the underwater and radiated airborne noise measurements. The measurements were done when the ships were in normal traffic, both during hybrid and electric propulsion mode.

A handheld class 1 sound level meter, Norsonic Nor 140, was used to record and analyze the sound level. A manual sweep of 30 seconds was used to get a spatial average of the sound in the measured rooms. No corner position was used due to the complexity of the room geometries and limited time. Both the active and the passive bridge were measured, and the presented values represent the energy averaged sound pressure level.

A list of the measured rooms and their equivalent A-weighted results are found in Table 15 and Table 16. The spectra of the measurements can be found in Figure 40–Figure 44.

Table 15. Onboard measured A-weighted sound pressure levels in different rooms onboard Aurora for her two propulsion cases, hybrid and electric.

Aurora	**Hybrid** L_{Aeq} (dB)	**Electric** L_{Aeq} (dB)
Bridges (both active and passive)	51	49
ECR	53	51
Thruster room (thruster 3 & 4)	98	95
Generator room (Generator 1)	106	76
Cabin (Chief officer)	48	44

Table 16. Onboard measured A-weighted sound pressure levels in different rooms onboard Tycho Brahe for her two propulsion cases, hybrid and electric.

Tycho Brahe	**Hybrid** L_{Aeq} (dB)	**Electric** L_{Aeq} (dB)
Bridges (both active and passive)	50	49
ECR	55	50
Thruster rooms (thruster 3&4)	91	93
Generator room (Generator 3)	104	75
Cabin (Chief engineer)	46	45

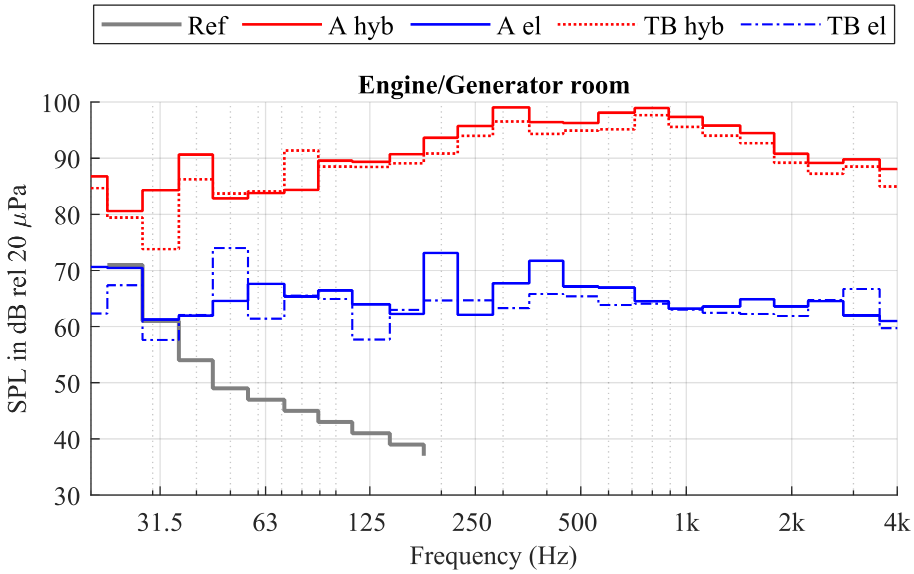

Figure 40. Onboard measured sound pressure levels in decidecade (1/3 octave) band levels in the engine/generator room. The "Ref" curve can be used as guidance when assessing the risk for disruption of low-frequency noise for working conditions with high demands on continuous concentration according to the Swedish Work Environment Authority. "A" represents Aurora and "TB" represents Tycho Brahe, both ForSea ferries.

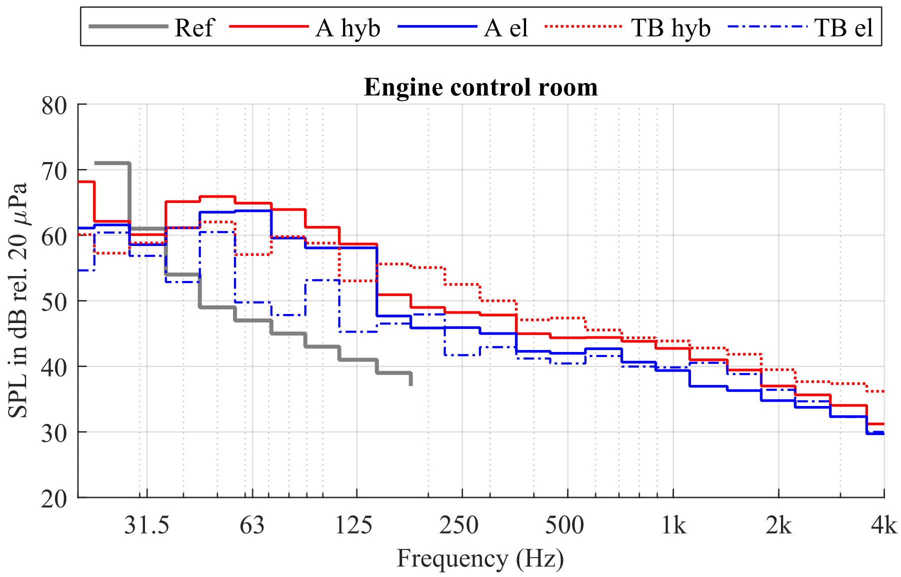

Figure 41. Onboard measured sound pressure levels in decidecade (1/3 octave) band levels in the engine control room. The "Ref" curve can be used as guidance when assessing the risk for disruption of low-frequency noise for working conditions with high demands on continuous concentration according to the Swedish Work Environment Authority. "A" represents Aurora and "TB" represents Tycho Brahe, both ForSea ferries.

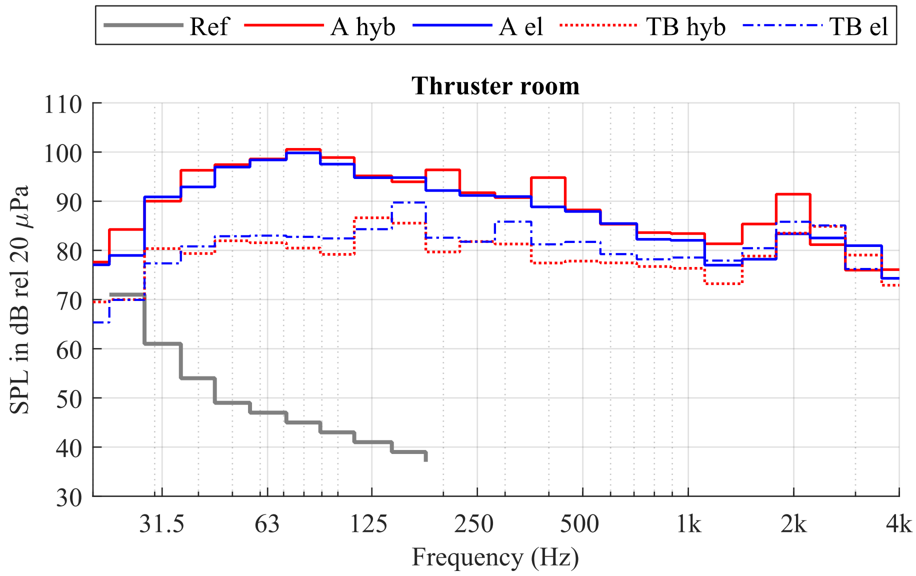

Figure 42. Onboard measured sound pressure levels in decidecade (1/3 octave) band levels in a thruster room. The "Ref" curve can be used as guidance when assessing the risk for disruption of low-frequency noise for working conditions with high demands on continuous concentration according to the Swedish Work Environment Authority. "A" represents Aurora and "TB" represents Tycho Brahe, both ForSea ferries.

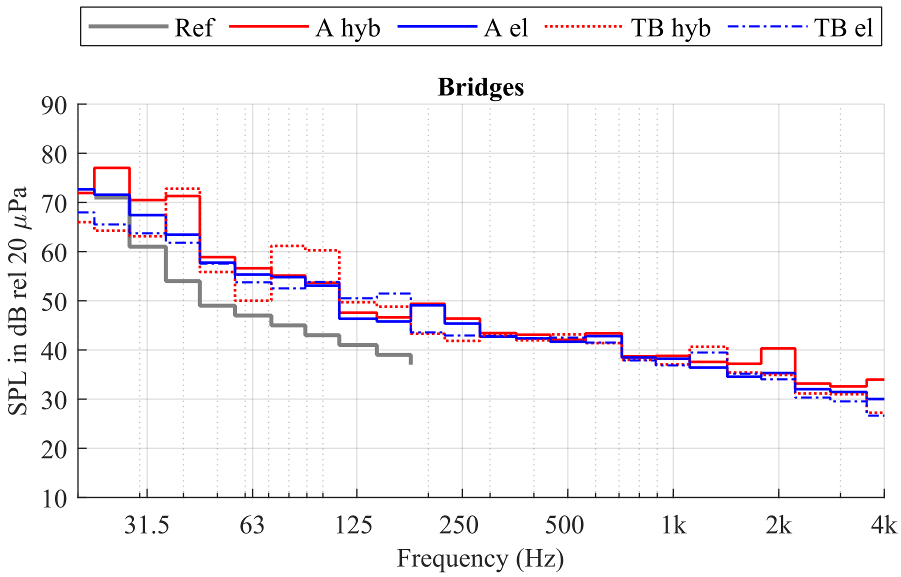

Figure 43. Onboard measured sound pressure levels in decidecade (1/3 octave) band levels on the bridges. The "Ref" curve can be used as guidance when assessing the risk for disruption of low-frequency noise for working conditions with high demands on continuous concentration according to the Swedish Work Environment Authority. "A" represents Aurora and "TB" represents Tycho Brahe, both ForSea ferries.

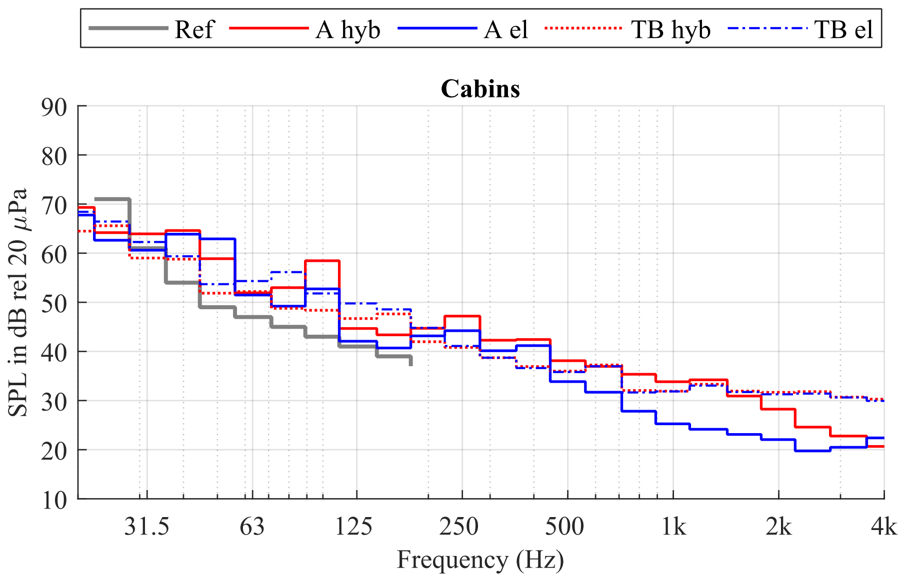

Figure 44. Onboard measured sound pressure levels in decidecade (1/3 octave) band levels in a crew cabin. The "Ref" curve can be used as guidance when assessing the risk for disruption of low-frequency noise for working conditions with high demands on continuous concentration according to the Swedish Work Environment Authority. "A" represents Aurora and "TB" represents Tycho Brahe, both ForSea ferries.

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B.4 Work and passenger environment

B.4.1 Work environment

Ten interviews were in total conducted via Teams. There was a mix of onboard responsibilities among the interviewees including deck, machinery and catering. Many of the interviewees had long experience.

The contents of the interviews are summarized in the following. We have focused on the essence of the answers. The interviewees wordings are here simplified and translated to English.

Summary

- Many perceive that noise and vibrations have decreased thanks to battery operation.
- The most significant reduction in noise has been on deck and in the engine room.
- The mentioned noise consists mostly of high-frequency sounds, alarms, radio, fans, and noises from passengers.
- On the bridge, there isn't a significant difference between battery and diesel, where instead it is the ventilation that is mostly heard.
- Vibrations are not seen as a problem, except for one person who believes it has worsened after the transition to battery operation.
- Most vibrations occur during mooring.

Perception of the work environment with respect to noise and vibrations

Noise has certainly become 30-40% lower with battery operation than before. Vibrations have also improved.	I feel that noise and vibrations have decreased with the transition to battery operation.	Ventilation fans on deck and chimneys are turned off during battery operation, so it is quieter.
I experience some vibrations all the time, but they have decreased with battery operation.	Driving with eco-driving is environmentally friendly and makes less noise and vibration.	After all these years, you get used to the sounds and vibrations, and it doesn't seem like a noticeable problem.

There are no major differences for the captain in the transition from diesel to battery, except for the power transmission and the absence of delays, reducing the experience of stress.	I think there is a high focus on safety, and it is constantly addressed and improved.	Needle guns used for rust knocking vibrate but have improved significantly.
Since there is not as much noticeable delay in power transmission, there is no need to brake as much.	Sound sources are the wind, guests, and music in the bar.	I feel a noticeable fatigue from noise after daytime shifts.
Guests can be very loud depending on the amount of alcohol consumed.	Most noise comes from guests around 12 and 14 o'clock and in the evenings.	Most noise comes from guests around 12 and 14 o'clock and in the evenings.
I experience continuous vibrations and a lot of noise from passengers who are alcohol-affected and celebrating. Some can behave unpleasantly and threatening.	A lot of noise from a radio where there is a lot of communication and various alarms are given.	Noise comes from thrusters and a lot of alarms, especially fire alarms are very loud, and car alarms.
Almost all personnel have impaired hearing at each checkup.	Noise occurs mostly in the engine room and on deck, some high-frequency sounds. Sound sources are pumps, fans, and electric motors.	The noise level is perceived as high when handling return glass, which happens several times during the day. When the provision elevator operates, which also happens several times a day, it sounds a lot. Noise has improved

		but can surely be further improved. One becomes very tired in the head when coming home.
I find that low-frequency sounds have become more distinct. Vibrations increase at higher speeds and upon arrival at the dock.	When docked, you stand for 6-7 minutes, and that's when the vibrations are more noticeable.	Most vibrations are experienced upon arrival and departure but also during rough weather and depending on who is driving.
I experience vibrations when the boat arrives at the dock during departure and arrival and feel that differences can be perceived depending on who is driving, weather conditions, and if there is a current.	One person feels that the vibrations have become more aggressive.	Car alarms have become so sensitive in the last 10 years that they trigger very easily during vibrations, and it's a sound source that is truly troublesome. Other sources of noise on deck include engine noise, wind, and people.

B.4.2 Passenger environment

The investigation onboard the ForSea ships was divided in two parts. Before lunch the Silent@Sea investigator was onboard Aurora which was running in electrical propulsion mode. After lunch the investigator changed to Hamlet which only operates in diesel propulsion. Different QR-codes were used to separate the answers from the different ships. A few passages with Aurora were made in hybrid mode and then the QR-code for Hamlet was used. In this way it was possible to separate the answers from the two modes even though it was not the same ship. Some passengers preferred to fill in the paper version of the questionnaire and these were afterwards transferred to the digital platform.

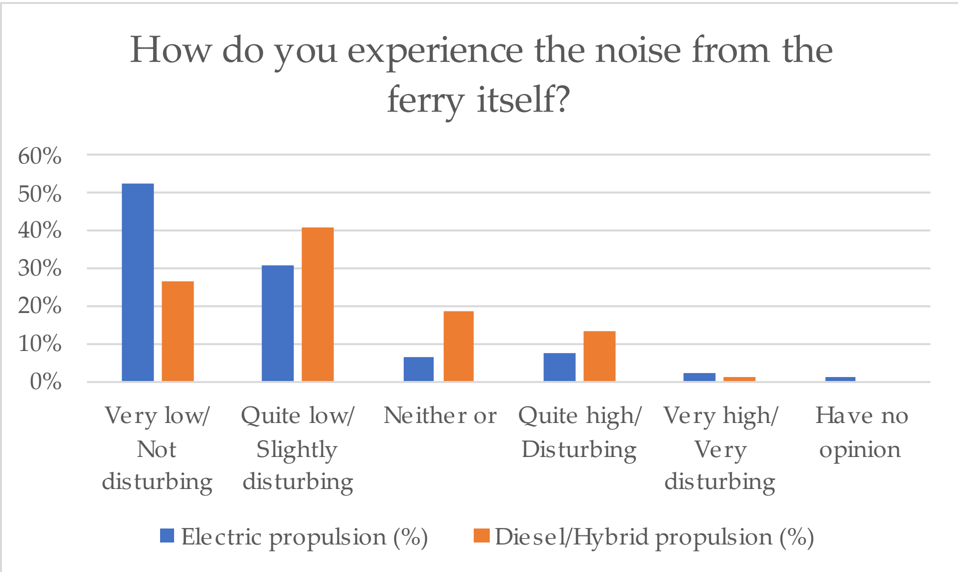
During electrical propulsion onboard Aurora 95 persons answered the questionnaire, 37 Danish and 58 Swedish. The number of respondents onboard Hamlet in diesel mode and Aurora in hybrid mode was 77, 29 Danish and 48 Swedish.

Summary

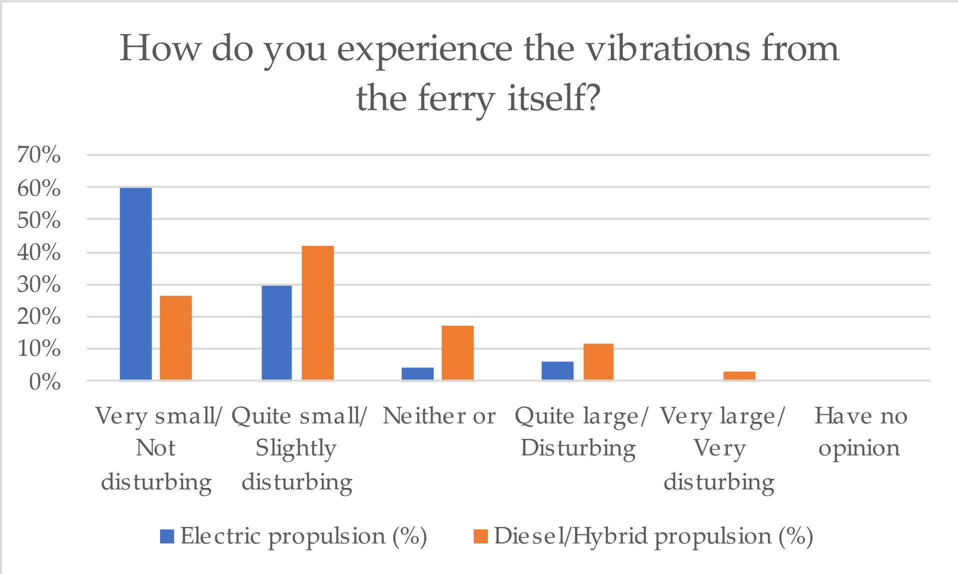
The majority of the passengers were not disturbed by the ferry's noise and vibrations, regardless of the propulsion mode. The results still show that the passengers' experience of noise and vibrations on board differs between electric and diesel(/hybrid) propulsion. More people were not disturbed by noise and vibrations during the electric propulsion.

The question about the comfort on board depicts a wide range of impressions, it was not only satisfaction with the ferry's own noise and vibrations that was captured in the answers. Passengers said, for example, that the loudspeaker calls are very loud, as was the music in the restaurant.

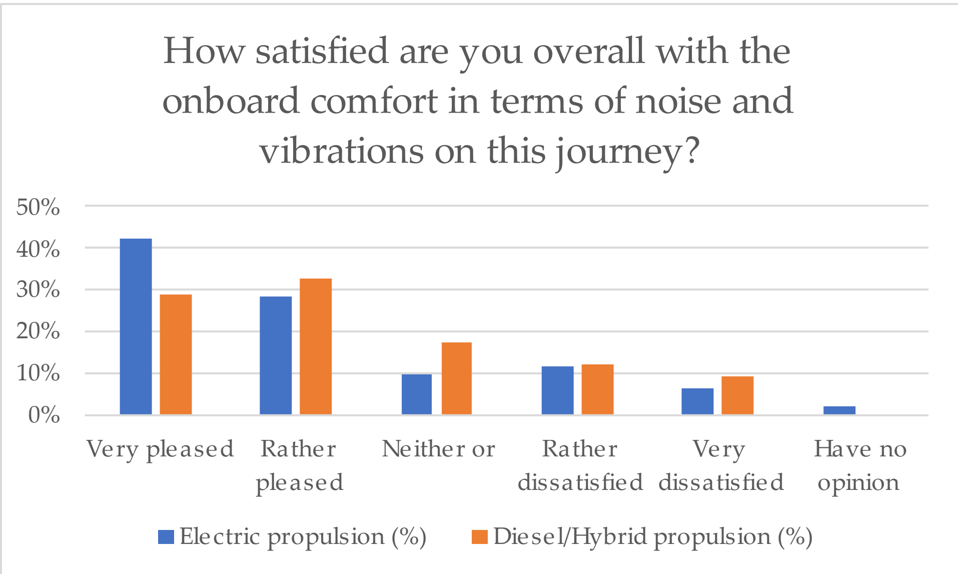
Questionnaire results



How do you experience the noise from the ferry itself?	Electric propulsion (%)	Hybrid propulsion (%)
Very low/ Not disturbing	53%	26%
Quite low/ Slightly disturbing	31%	41%
Neither or	6%	18%
Quite high/ Disturbing	7%	13%
Very high/ Very disturbing	2%	1%
Have no opinion	1%	0%



How do you experience the vibrations from the ferry itself?	Electric propulsion (%)	Hybrid propulsion (%)
Very small/ Not disturbing	60%	26%
Quite small/ Slightly disturbing	29%	42%
Neither or	4%	17%
Quite large/ Disturbing	6%	12%
Very large/ Very disturbing	0%	3%
Have no opinion	0%	0%



How satisfied are you overall with the onboard comfort in terms of noise and vibrations on this journey?	Electric propulsion (%)	Hybrid propulsion (%)
Very pleased	42%	29%
Rather pleased	28%	33%
Neither or	9%	17%
Rather dissatisfied	12%	12%
Very dissatisfied	6%	9%
Have no opinion	2%	0%

Other aspects reported by the passengers

- Many were very disturbed by the loudspeaker calls, which were perceived as too loud.
- The music played was considered too loud by several.
- The ferries are much quieter now than in the past.
- All ferries run on batteries and are silent, several people thought.
- It is not environmentally friendly to hand out a plastic pen to everyone who gets a ticket at Hamlet.
- Hamlet is the purest ferry, big difference from Tycho Brahe.
- Ticket price of 150 SEK is too high considering that it is such a short journey.
- Deteriorated tour list compared to before, does not fit with working hours.

About the respondents

Most, 45%, rarely travel with ForSea's ferries. 35% travel a few times per week and 6% travel once per week. 12% travel a few days per month.

Most, 38%, were commuters to and from work or study. 14% travelled for work. 27% made a leisure trip, 11% travelled as tourists and 10% made another type of trip, e.g., purchasing alcohol.

Most, 43% were in the 40-59 age range. The second largest category, 20-39 years made up 32%. 18% were between 60-79 years old. Of those who answered the survey, 6% were aged 19 or under and 0.6% were aged 80 or over.

The questionnaire was answered by slightly more men than women (57% and 41%, respectively). The others did not want to state or chose a different gender.

The investigators observations

- Aurora had more commuters (morning and morning trips) compared to Hamlet (afternoon and early evening).
- Hamlet had more people who made a leisure trip or other trip (after lunch to afternoon) "tour", buy beer, drink beer.
- There were more men than women on board.
- Hamlet had slightly older travelers.
- It was quite difficult to get answers from passengers on Hamlet.
- Relatively many respondents wanted to use a paper survey instead of a digital survey because they were unfamiliar with the technology or unsure of using a QR code.

C Färjerederiet – hybrid vs electrical propulsion on road ferries

C.1 Introduction

The Färjerederiet case study was performed in 2022 and 2023. An initial visit to the ships was performed in March 2022. Crew interviews and passenger surveys were performed 20 March 2023. The radiated noise measurements (Table 17 and Table 18) were performed 7-9 June 2023 together with onboard noise and vibration measurements.

Table 17. Färjerederiet radiated noise measurement log (Neptunus).

Time	Propulsion	Propeller rpm	Distance to hydrophones	Distance to microphones	Included in analysis
21:34	Diesel	240	105 m	69 m	No
21:51	Diesel	240	105 m	69 m	Yes
22:04	Diesel	240	107 m	70 m	Yes
22:26	Diesel	240	105 m	69 m	Yes
23:03	Diesel	240	112 m	85 m	Yes
23:26	Diesel	240	114 m	78 m	Yes
23:41	Diesel	240	112 m	75 m	Yes
23:44	Diesel	240	142 m	106 m	No
00:04	Diesel	190	104 m	67 m	Yes
00:28	Diesel	190	118 m	81 m	Yes
01:03	Diesel	190	102 m	65 m	No
01:28	Diesel	190	104 m	67 m	Yes
02:04	Diesel	190	94 m	57 m	Yes
02:29	Diesel	190	103 m	67 m	Yes
04:05	Diesel	190	104 m	67 m	Yes
04:28	Diesel	190	107 m	70 m	No
05:03	Diesel	190	115 m	78 m	No
05:22	Diesel	190	103 m	67 m	Yes
05:34	Diesel	190	98 m	61 m	Yes

Table 18. Färjerederiet radiated noise measurement log (Tellus).

Time	Propulsion	Propeller rpm	Distance to hydrophones	Distance to microphones	Included in analysis
21:03	Electric	240	125 m	88 m	No
21:34	Hybrid	240	126 m	89 m	Yes
21:52	Hybrid	240	97 m	61 m	Yes
22:04	Hybrid	240	117 m	81 m	Yes
22:26	Electric	240	96 m	60 m	Yes
23:04	Electric	240	109 m	72 m	No
23:27	Hybrid	240	105 m	69 m	Yes
23:38	Hybrid	240	105 m	69 m	Yes
23:42	Hybrid	240	101 m	65 m	Yes
00:03	Electric	240	111 m	74 m	Yes
00:27	Electric	240	100 m	63 m	Yes
01:04	Electric	240	107 m	71 m	Yes
01:27	Hybrid	240	108 m	71 m	Yes
02:04	Electric	190	99 m	62 m	Yes
02:27	Electric	190	107 m	71 m	Yes
04:04	Hybrid	190	104 m	67 m	No
04:28	Hybrid	190	101 m	64 m	Yes
05:04	Hybrid	190	121 m	84 m	Yes

The positions of the measurement track and noise sensors are presented in Table 19 below.

Table 19. Positions of measurement track and sensors for the Färjerederiet radiated noise measurements.

Position	Coordinates
Measurement track, start	58° 18.143' N 11° 30.583' E
Measurement track, end	58° 18.150' N 11° 30.978' E
SilentRaft	58° 18.1722' N 11° 30.8389' E
Hydrophones	58° 18.2046' N 11° 30.8389' E

Figure 45 presents photos from the Färjerederiet study.

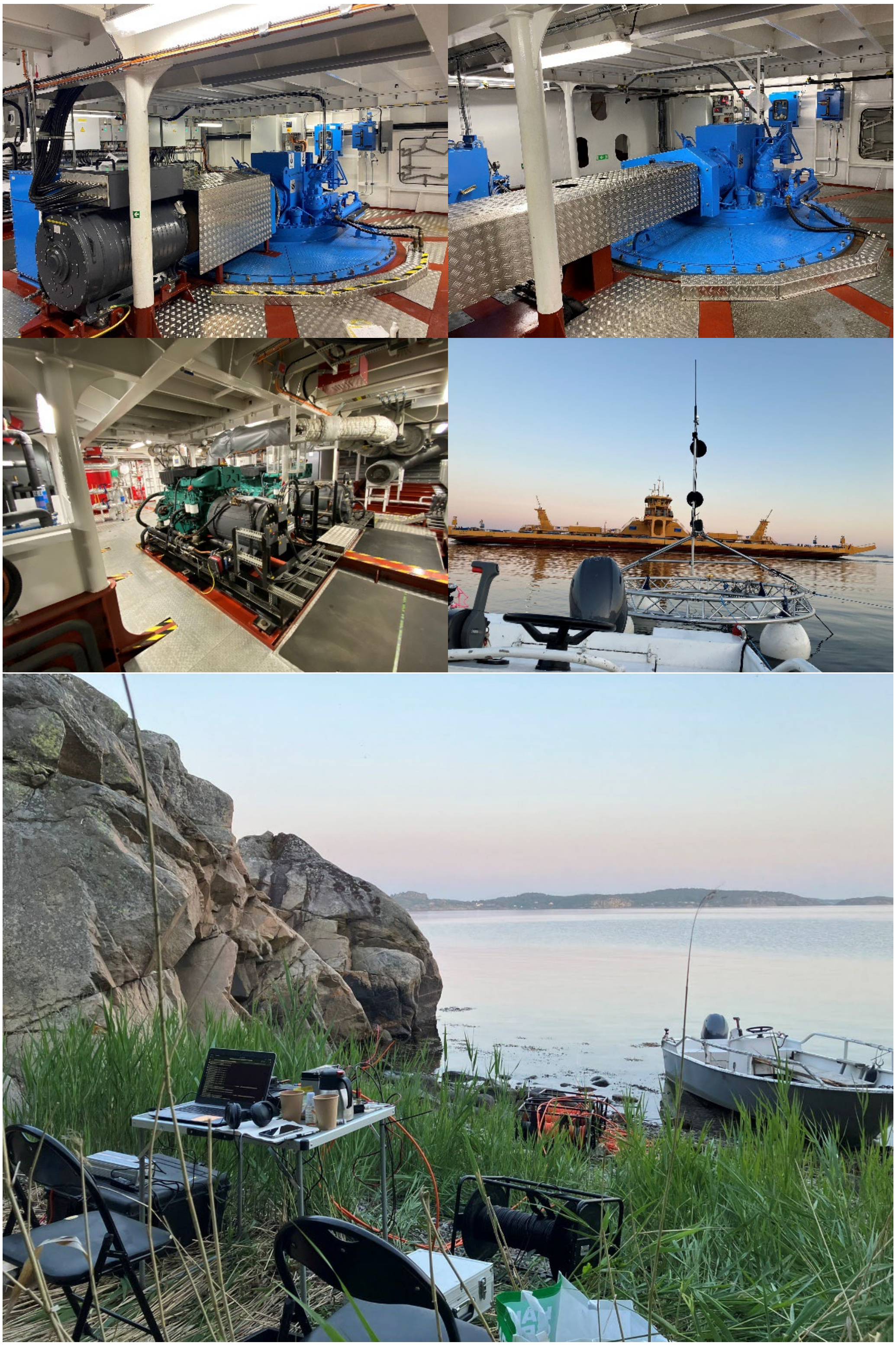


Figure 45. Photos from the Färjerederiet study. Thruster with shaft on Tellus (top left, with electrical motor) and on Neptunus (top right). Two engines with generators on Tellus (middle left). Ferry passing the SilentRaft (middle right). The measurement site (bottom).

C.2 Radiated noise

C.2.1 Airborne noise

For Färjerederiet the two ferries Neptunus and Tellus were measured. As only Tellus is able to switch between fully electric and hybrid modes it is the only one that can be analyzed in a similar manner as the previous cases. As shown in Figure 46, the corresponding difference between electric and hybrid modes is about 12 dB in the 63 Hz band. However, most of the measurements were done with the funnels facing away from the microphones, due to that the ferry cannot moor if turned in the other direction as it isn't symmetric across the length axis.

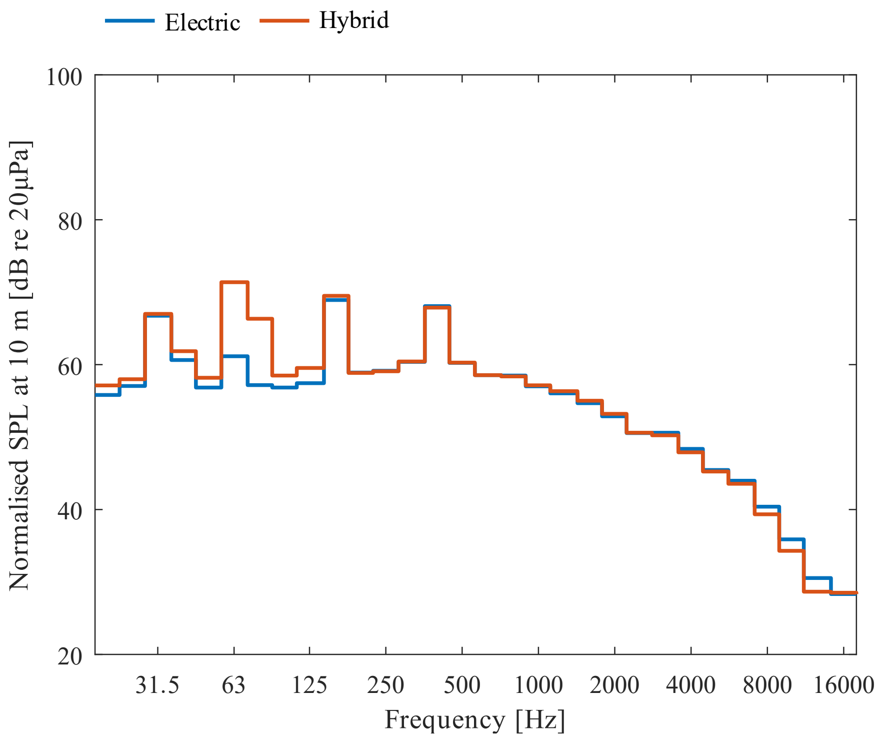


Figure 46. 1/3 octave band spectra of airborne noise from Tellus under electric and hybrid propulsion modes.

For a few passages the ferry was turned without mooring in between passages and the results show that the level of the 63 Hz band is even more prominent in hybrid mode, resulting in a difference of more than 20 dB between modes of propulsion. Figure 47 shows a 1/3 octave band comparison between electric mode with funnels facing away from the microphones and hybrid mode with funnels facing towards the microphones.

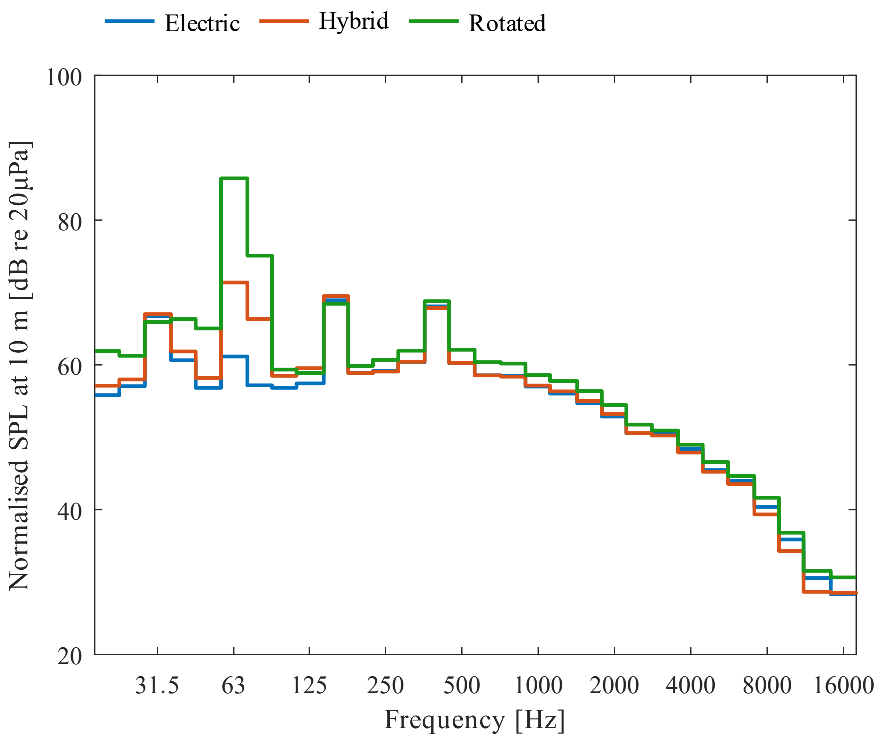


Figure 47. 1/3 octave band spectra of airborne noise from Tellus under electric and hybrid propulsion modes, with an additional spectrum for the two passages with Tellus rotated so that the funnels were facing the microphones.

Neptunus is not equipped for hybrid propulsion mode so no such comparison can be made, but reducing the speed could be a way to reduce the energy and thus potentially the radiated noise. Figure 48 shows 1/3 octave band spectra for Neptunus running at a propeller revolution speed of 190 rpm versus the normal cruising speed condition at 240 rpm. As can be expected the prominent level peaks corresponding to the engine fundamental frequency and first harmonic are shifted downward in frequency with reduced rotational speed. There seems to be a tendency that the overall level is slightly reduced at lower speed. However, the engine related peak levels are not reduced overall, but show a surprising increase for the first harmonic. This might be due to the engine harmonic coinciding with some resonance frequency of the exhaust system which indicates that to achieve a desired reduction in radiated airborne noise from reducing vessel speed, care needs to be taken to design the exhaust system to avoid such resonant behavior.

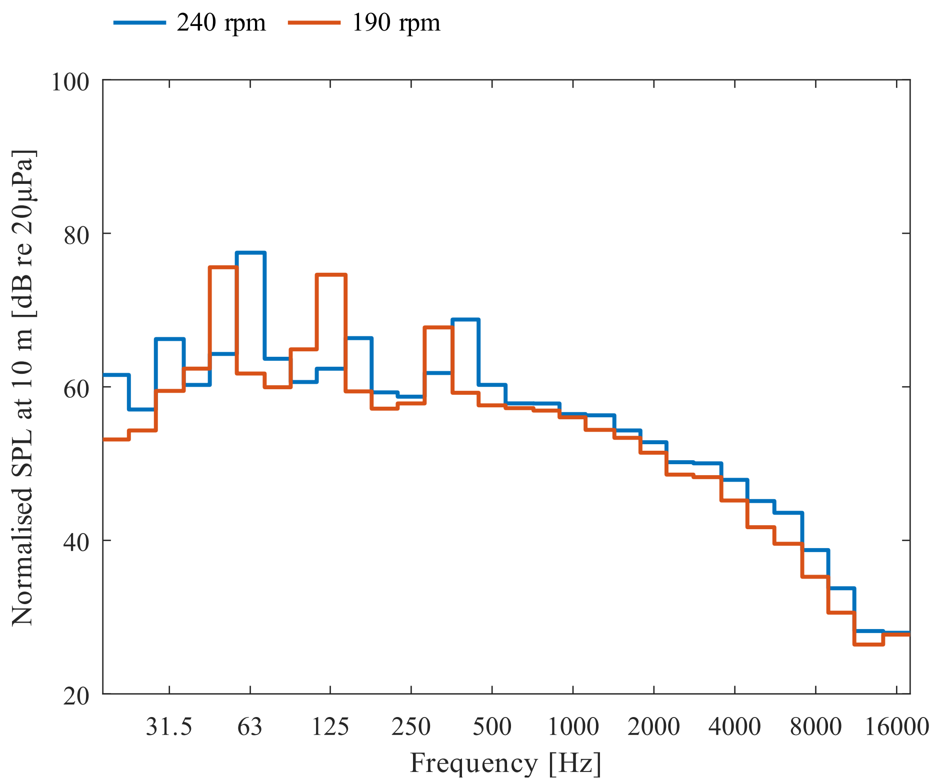


Figure 48. 1/3 octave band spectra of airborne noise from Neptunus under running at different propeller revolution speeds.

C.2.2 Underwater noise

The underwater radiated noise that was measured from Tellus with diesel-electric generator operating "hybrid mode" and turned off "electric mode" is shown in Figure 49. These results give a strong indication that the generator itself does not contribute to the underwater noise in a strong way. It is also clear that the results were very repeatable during the measurement, typically with only 3 dB spread between individual passages.

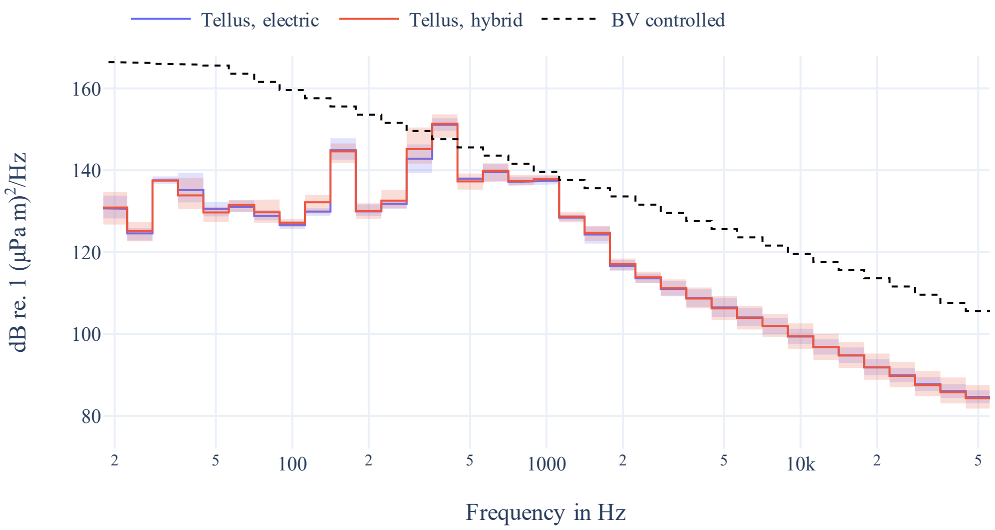


Figure 49. Underwater radiated nosie from Tellus in electric and hybrid mode. The shading indicate the largest spread of noise levels between the measured passages.

Comparing Tellus with her sister ship Neptunus, Figure 50 shows that Neptunus is typically a couple dB louder in the frequency region between 50 Hz and 400 Hz. In this region Neptunus has a quite even noise profile, while Tellus has a single band, the 160 Hz band, which is a lot noisier than the others.

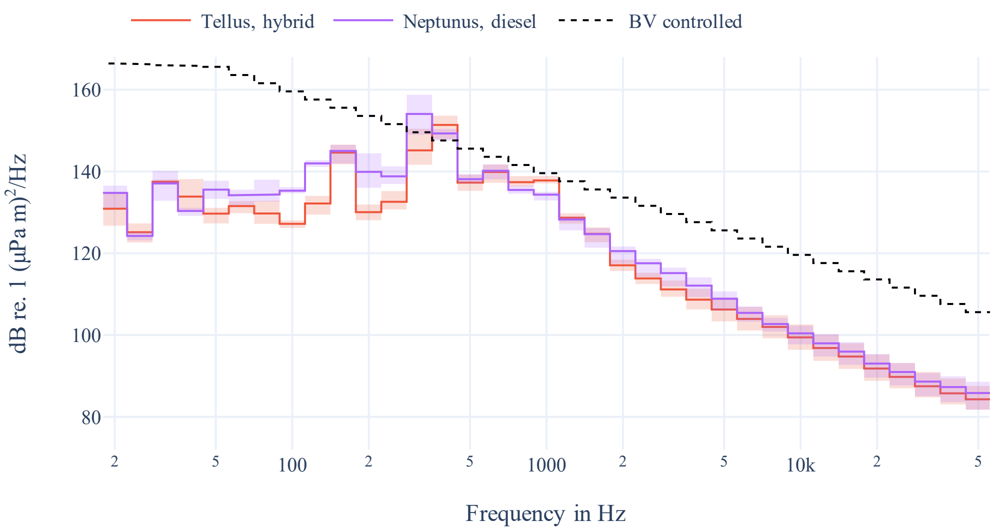


Figure 50. Underwater radiated noise from sister vessels Tellus and Neptunus. The shading indicate the largest spread of noise levels between measured passages.

Both Tellus and Neptunus were also measured in two speeds, targeting propeller rotation rates of 240 RPM and 190 RPM. This corresponds to a normal “daytime” cruising speed of 8 knots and a normal “nighttime” speed of 6.5 knots. The results for Tellus, in Figure 51, show that two of the frequency regions with high noise levels move to lower frequencies, with the 160 Hz band level shifting to the 125 Hz band, and the two strong bands at 315 Hz and 400 Hz seemingly combining to only the 315 Hz band. This is expected since the shift from 240 RPM to 190 RPM corresponds almost perfectly to one 1/3 octave, moving strong tonal components down approximately one 1/3 octave band. However, the same data for Neptunus, shown in Figure 52, does not show this frequency shift as clearly. This is likely due to the single strong band at 160 Hz apparent in Tellus’ source spectrum when operating at 240 RPM, whilst Neptunus has a more evenly distributed noise. Looking at the radiation from both ships above 1 kHz, the levels are decreased when sailing at a slower speed. This can be explained by the lower loading of the propellers, matching the reduced speed and power. To quantify the high frequency noise level reduction from this speed reduction, the median level decrease is calculated in the frequency range from the 1250 Hz band to the 10 kHz band. In this range Tellus is around 6 dB quieter while Neptunus is around 10 dB quieter. Typical noise source models estimate that the radiated noise decrease as $60 \log_{10} v/v_{ref}$, which for this RPM reduction would give a 6 dB reduction. We choose to calculate the reduction based on the RPM instead of the actual speed since the speed was more varied during the trials but calculating based on the speed give between 5 dB and 9 dB reduction. Seen as a whole, this speed decrease gives the expected noise reduction at high frequencies, while only moving the noise energy at lower frequencies.

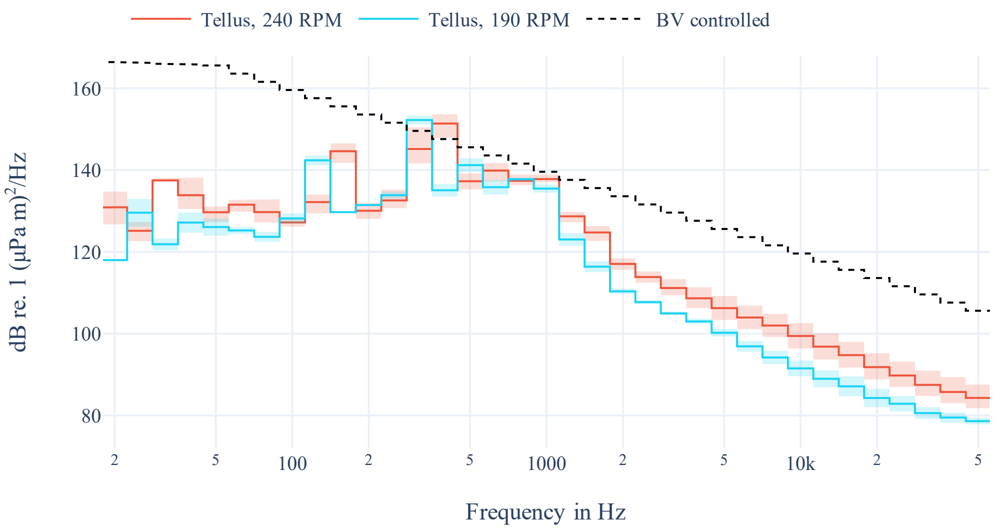


Figure 51. Underwater radiated noise from Tellus operating with diesel generator, running the propellers at 240 RPM and 190 RPM. The shading indicate the largest spread of noise levels between measured passages.

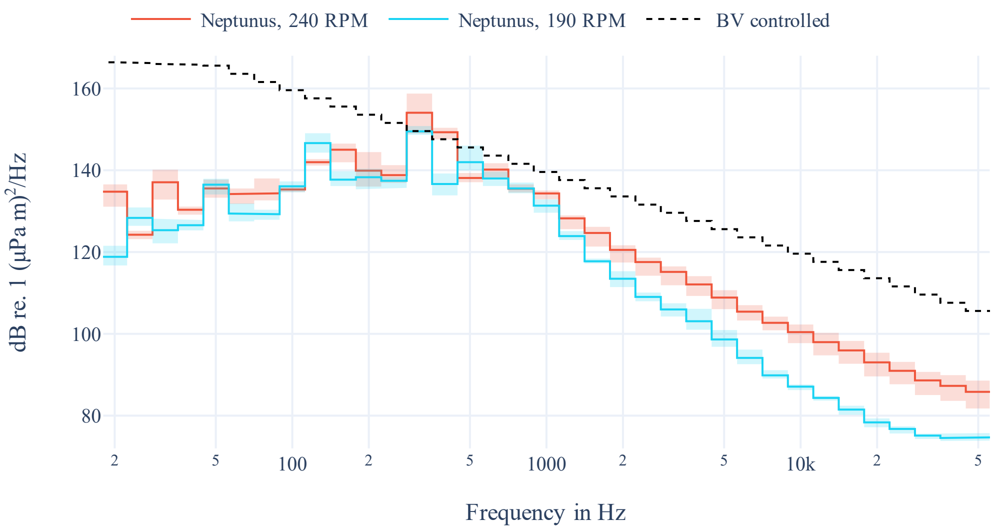


Figure 52. Underwater radiated noise from Neptunus, running the propellers at 240 RPM and 190 RPM. The shading indicate the largest spread of noise levels between measured passages.

C.2.3 Noise sources

The received noise level is shown with high frequency resolution for Tellus and Neptunus in Figure 53 through Figure 56. These figures show the results in air and in water in the two rows, and the electric and hybrid cases as two lines in each axis.

Each measured speed is shown in a separate figure. The identified tones are also shown in these figures, by coloring each peak with the corresponding color.

Starting with the results for Tellus in 240 RPM, shown in Figure 53, the airborne tones from the diesel generator are very clear from comparing the fully electric and hybrid cases. This diesel generator is operating at around 1300 RPM, which corresponds to 21.6 Hz. This frequency has a clear peak in the airborne noise, as well as the second-order harmonic at 43.3 Hz, but the strongest component is the third-order harmonic around 65 Hz. This can be explained since the diesel engine is a six-cylinder four-stroke construction, which has ignitions three times per revolution. Clearly visible in both electric and hybrid mode is the propeller blade pass frequency at 16 Hz and its second-order harmonic at 32 Hz. Similarly, the harmonics for the electric motor are visible at 20 Hz, 40 Hz, and 60 Hz.

In addition to these identified components, there are two strong tones at 29.8 Hz and 36.2 Hz which could not be directly attributed as harmonics to either the electrical motor, the diesel generator, or the blade passing frequency. Comparing the relation between the propeller tone at 32 Hz and the unknown tone at 29.8 Hz with the results from Tellus in 190 RPM, there are corresponding tones at 23.6 Hz and 25.6 Hz at the slower speed. It therefore seems likely that this tone is generated by some machine related to the propulsion, geared close to a 3:2 ratio to the electrical motor.

The results for Tellus in 190 RPM share many features to the results in 240 RPM, but with tones from the propeller and electrical motor shifted down by 24/19, as expected. The tones from the generator are not shifted in frequency, since it is decoupled from the speed of the propeller and only related to the overall energy needs of the ship.

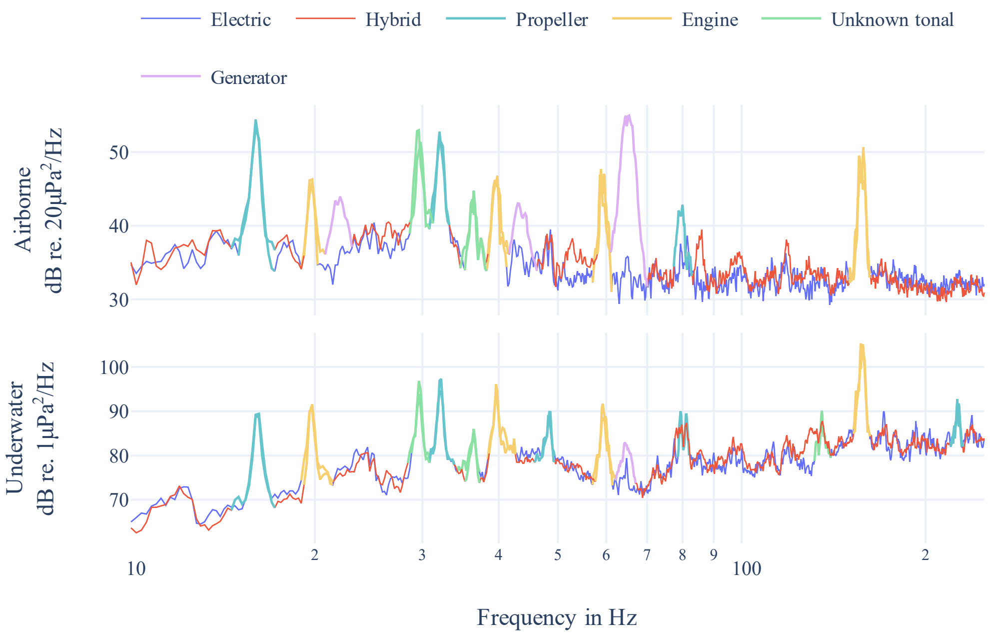


Figure 53. Identified tones for Tellus in 240 RPM.

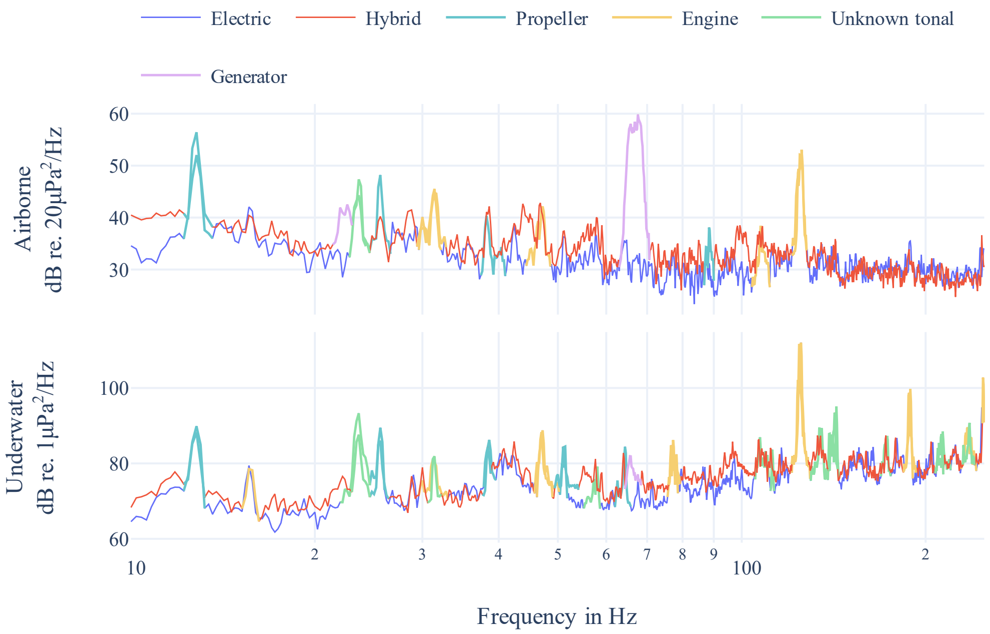


Figure 54. Identified tones for Tellus in 190 RPM.

The results from Neptunus, shown in Figure 55 for 240 RPM and Figure 56 for 190 RPM, have many similarities with the results from Tellus in electric mode.

Most notably, the tones from the propeller seem almost identical from the two ships, strengthening the notion that the ships are close sister vessels. The engine harmonics on Neptunus occur at the same frequencies as those from Tellus, but typically at a higher level. This is not unexpected, since Neptunus operates its four diesel engines instead of the two electrical motors used by Tellus, whilst all other mechanical components, e.g., gearboxes, are the same for the two ships. In particular the airborne third-order harmonic (at 60 Hz in 240 RPM and 48 Hz in 190 RPM) is much stronger for Neptunus, which is expected since this is the diesel ignition frequency and replaces the strong 65 Hz component from the generator in Tellus. Additionally, the overall underwater level difference in the 50 Hz to 250 Hz range, clearly seen in Figure 50, can also be seen in this higher resolution. This difference does not seem to be caused by particularly dominant tones, but instead an overall higher broadband level radiated from Neptunus.

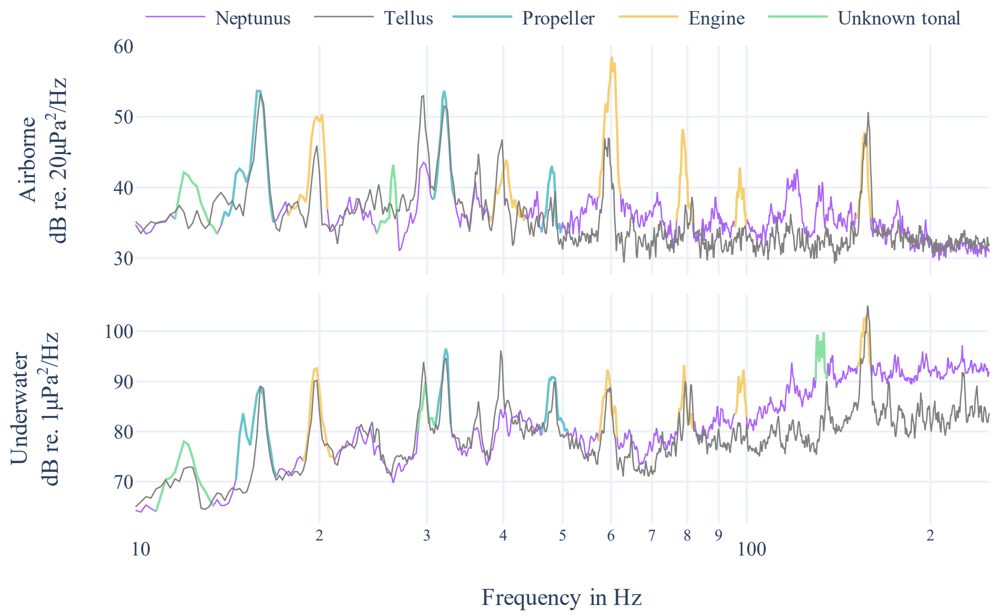


Figure 55. Identified tones for Neptunus in 240 RPM, compared to Tellus in electric mode.

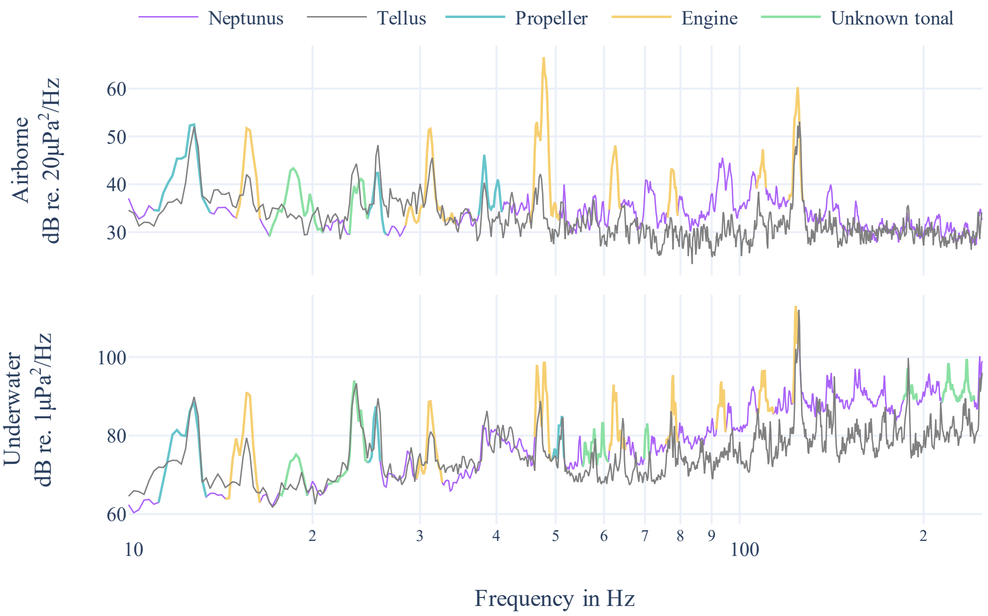


Figure 56. Identified tones for Neptunus in 190 RPM, compared to Tellus in electric mode.

The relative power distributions for these measurements are shown in Figure 57 for Tellus. As expected, the dominant source in air is the diesel generator, followed by components from the engine. In the water, the dominant source is also related to the propulsion engine, whilst the diesel generator only has a minor effect. This noise comes mainly from the 8th-order harmonic (at 160 Hz in 240 RPM and 125 Hz in 190 RPM). This tone is present at almost the same strength in Neptunus as well, which rules out the actual engine as the source. This means that the noise likely comes from some mechanical source directly linked to the shaft, e.g., the gearbox or some supporting machine.

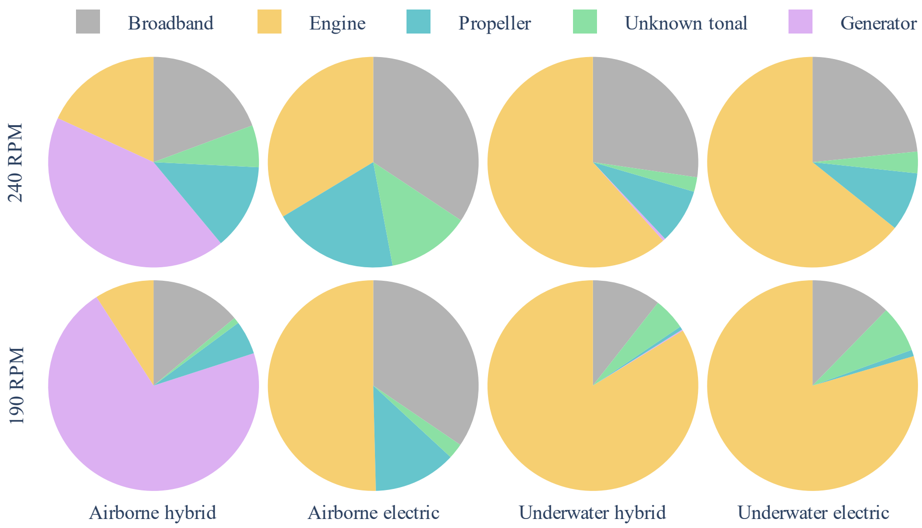


Figure 57. Noise power distribution for Tellus.

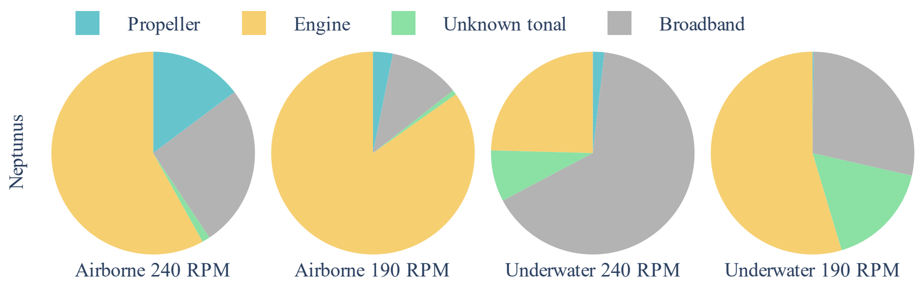


Figure 58. Noise power distribution for Neptunus.

C.3 Onboard noise

Onboard noise was measured at the same time as the underwater and airborne (outdoor) noise measurements at 240 rpm.

A handheld class 1 sound level meter, Nor 140, was used to record and analyze the sound level. A manual sweep of 30 seconds was used to get a spatial average of the sound in the measured rooms. No corner position was used due to the complexity of the room geometries and limited time. Both the thruster room in the bow and in the stern were measured, as well as engine rooms in the bow and the stern, and the presented values represent the energy averaged sound pressure level.

A list of the measured rooms and their equivalent A-weighted results are found in Table 20 and Table 21. The spectra of the measurements can be found in Figure 59–Figure 61.

Table 20. Onboard measured A-weighted sound pressure levels in different rooms onboard Tellus for her two propulsion modes, hybrid and electric.

Tellus	Hybrid L_{Aeq} (dB)	Electric L_{Aeq} (dB)
Bridge	38	38
Thruster rooms	96	96
Engine rooms	104	75

Table 21. Onboard measured A-weighted sound pressure levels in different rooms onboard Neptunus for her one propulsion mode, diesel.

Neptunus	Diesel L_{Aeq} (dB)
Bridge	43
Thruster rooms	97
Engine rooms	105

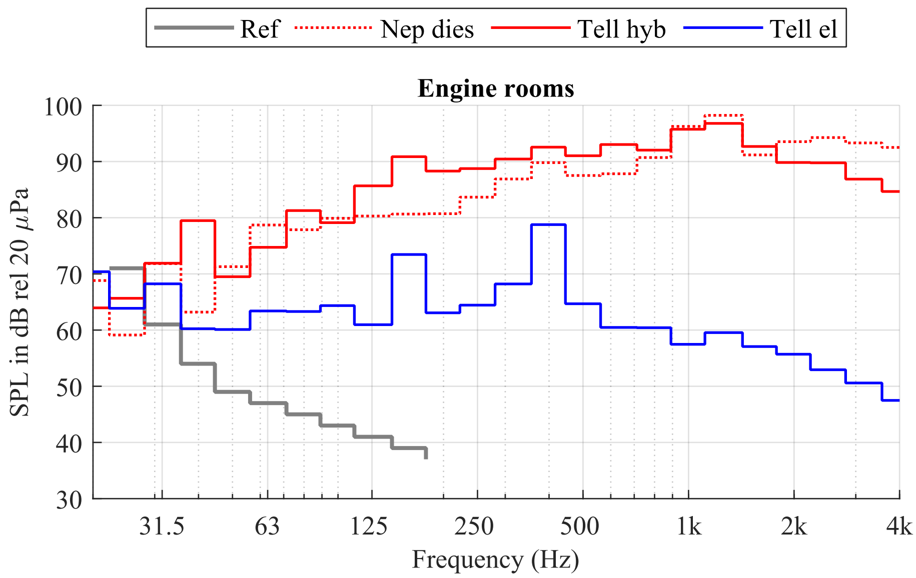


Figure 59. Onboard measured sound pressure levels in decidecade (1/3 octave) band levels in the engine/generator room. The "Ref" curve can be used as guidance when assessing the risk for disruption of low-frequency noise for working conditions with high demands on continuous concentration according to the Swedish Work Environment Authority. "Nep" represents Neptunus and "Tell" represents Tellus, both Färjerederiets road ferries.

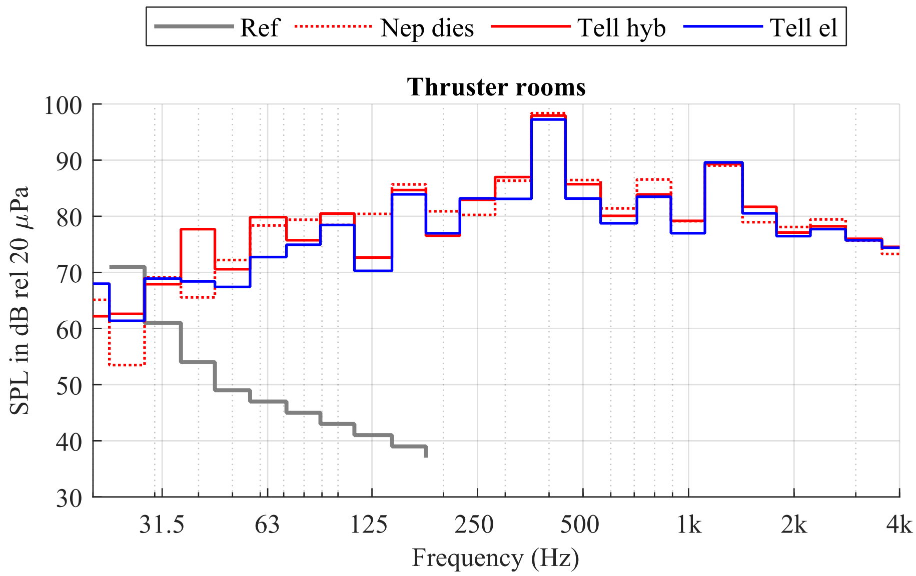


Figure 60. Onboard measured sound pressure levels in decidecade (1/3 octave) band levels in the thruster rooms. The "Ref" curve can be used as guidance when assessing the risk for disruption of low-frequency noise for working conditions with high demands on continuous concentration according to the Swedish Work Environment Authority. "Nep" represents Neptunus and "Tell" represents Tellus, both Färjerederiets road ferries.

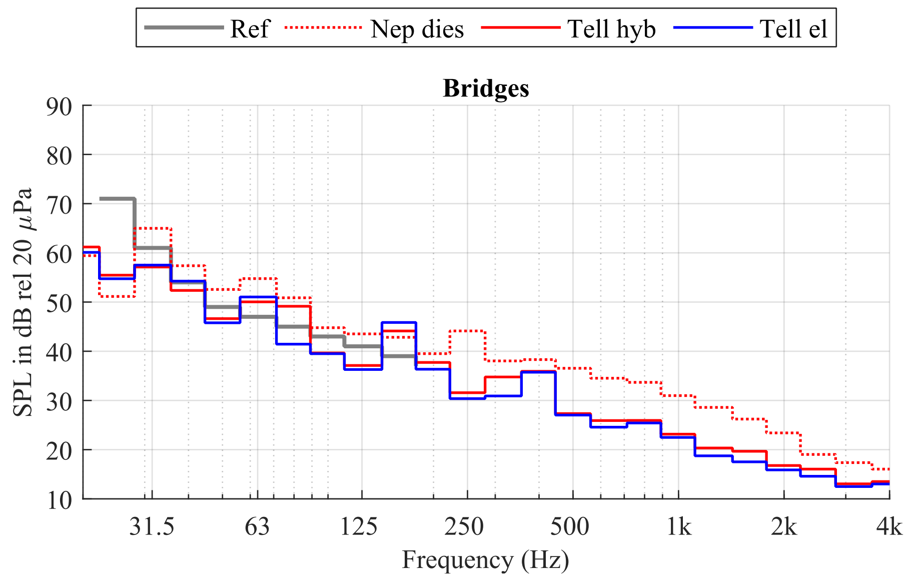


Figure 61. Onboard measured sound pressure levels in decidecade (1/3 octave) band levels on the bridge. The "Ref" curve can be used as guidance when assessing the risk for disruption of low-frequency noise for working conditions with high demands on continuous concentration according to the Swedish Work Environment Authority. "Nep" represents Neptunus and "Tell" represents Tellus, both Färjerederiets road ferries.

C.4 Work and passenger environment

C.4.1 Work environment

Four interviews were conducted on site. The interviewees had varying background and experience from other types of ships.

The contents of the interviews are summarized in the following. We have focused on the essence of the answers. The interviewees wordings are here simplified and translated to English.

Summary

- The crew is satisfied with the working environment overall.
- Both ferries are quieter than older ferries they have worked on.
- There is not a significant difference on the bridge, but there is a difference in the engine between the two ferries.
- Tellus makes a lot of noise at the quay when charging the batteries.
- The radar was mentioned by several, a loud sound that can be heard on the Neptune bridge.
- Ventilation can be heard, and the machinery room under the bridge was also mentioned in connection with noise.
- Some vibrations during mooring, when braking heavily and from waves.
- Overall, no one is bothered by the vibrations.
- Work environment risks are not specifically linked to noise and vibrations but rather to falls, crushing, and vehicle stowage.

Perception of the work environment with respect to noise and vibrations

The engines are so quiet that you can hear the radar.	Vibration-wise, there is nothing, but we do have very short trips.	The worst noise is on Neptune, and the radar makes a dreadful noise when activated.
Incredibly good working environment here.	When lowering the hydraulic ramp, weighing 20 tons, there is a loud bang.	If you don't achieve a smooth mooring and can't reduce the speed, you may experience an

		impact and noise against the diving bollards.
The loudest sound occurs when Tellus is being charged at the quay by the engine.	The control cabin – I have somehow come to believe that it is quieter on Tellus.	The radar operates too fast on Neptune and makes noise.
Electric motors make more noise than expected during operation.	Tellus has only one engine running, and it makes more noise because it operates at high intensity constantly.	Lower and quieter environment on the ferries compared to other vessels. What strikes me is that the ventilation creates some noise.
I find it absolutely fantastic, with low noise.	On Neptune, radar noise is most noticeable during regular operation.	It's very safe and nice here.
Tellus has only one auxiliary engine compared to Neptune with four engines. Tellus is more noise friendly.	On the bridge, regardless of the boat, you don't notice a huge difference. It's the engine noise that is audible.**	Even though Neptune creates more noise, there is a significant difference compared to older vessels.
	There are vibrations, of course, but nothing you think about.	Vibrations occur: 1. Cavitation from the propeller if you brake and need to stop quickly. It creates a vacuum that causes vibrations. 2. In open waters, large waves occur. The shaking of the waves can cause vibrations that propagate, shaking and making noise in the control cabin.

		3. If something gets stuck in the propeller jet. Ropes etc. – if it gets jammed, it can vibrate. Divers are called in to check. This occurs every year.

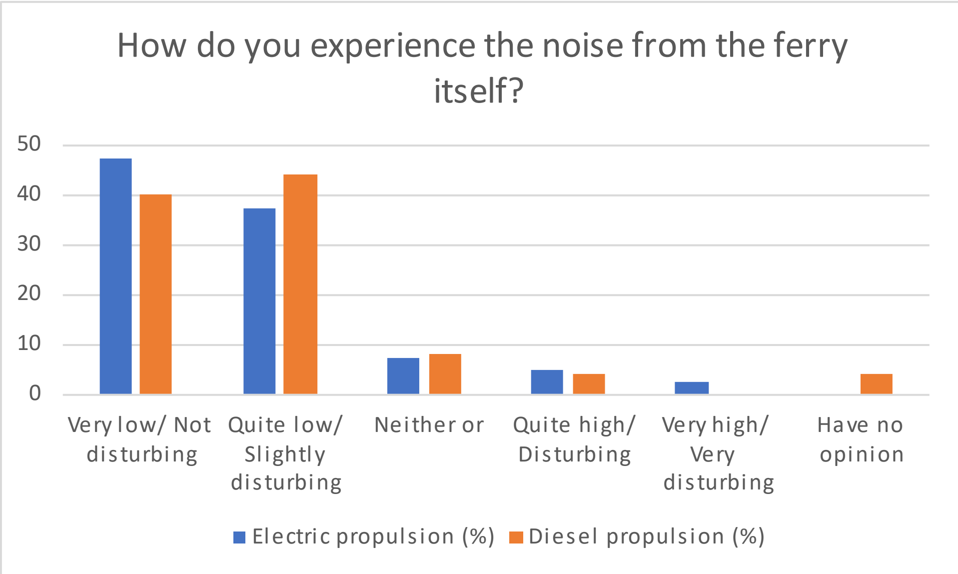
C.4.2 Passenger environment

To separate the two propulsion modes for Färjerederiet's road ferries trafficking Gullmarn, the investigation was conducted on Tellus for the electric mode and on Neptunus for the diesel-mode. Different QR-codes were provided to the passengers to separate the answers from the two modes. During electrical propulsion on Tellus 40 persons answered the questionnaire, compared with the diesel mode on Neptunus where 25 persons answered, in total 65.

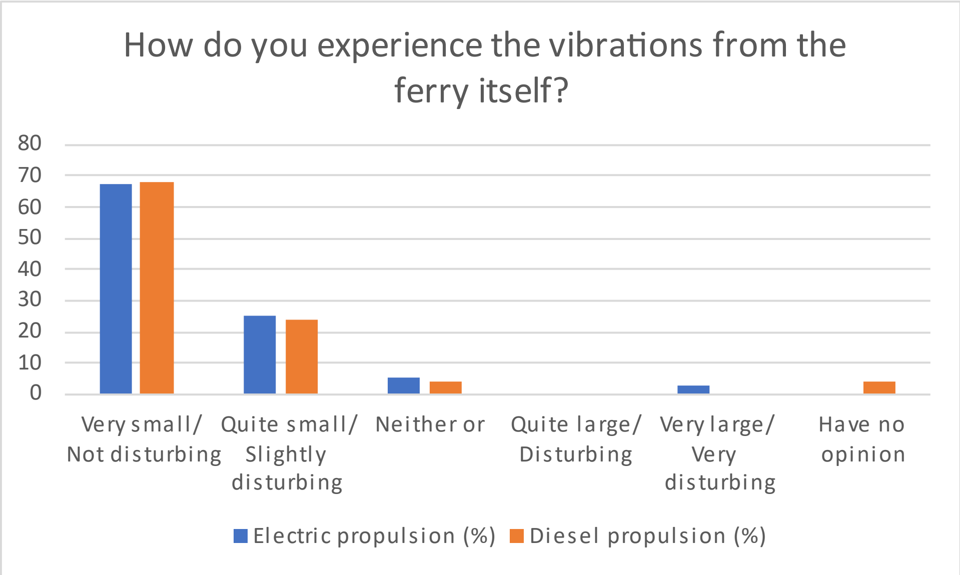
Summary

The results indicate that there is no significant difference regarding noise and vibrations between the two different road ferries from a passenger point of view. The ferries are perceived as quiet regardless of the propulsion mode. Since passengers were mostly inside their vehicles during the investigation, as it was cold outside, they did not perceive much noise from the ferry.

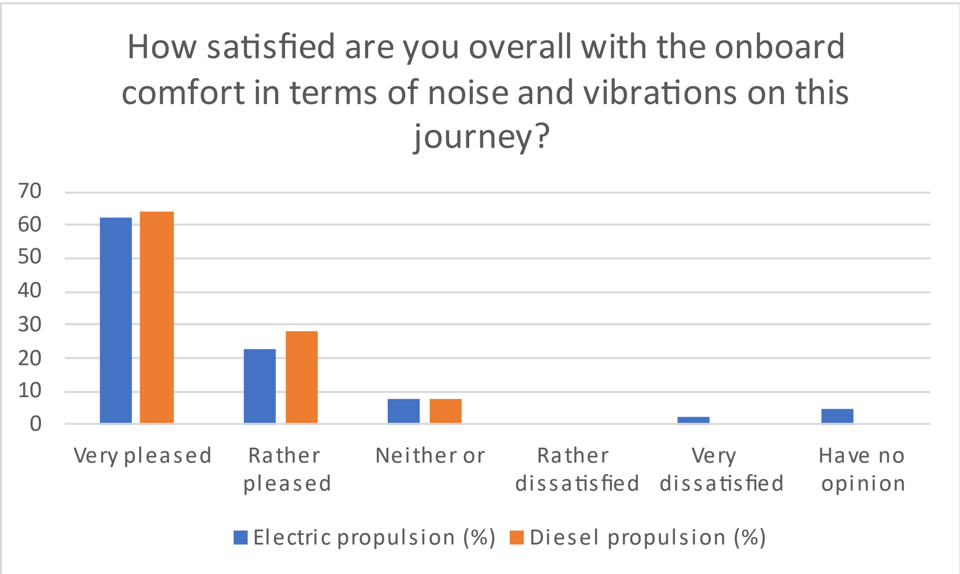
Questionnaire results



How do you experience the noise from the ferry itself?	Electric propulsion (%)	Hybrid propulsion (%)
Very low/ Not disturbing	48	40
Quite low/ Slightly disturbing	38	44
Neither or	8	8
Quite high/ Disturbing	5	4
Very high/ Very disturbing	3	0
Have no opinion	0	4



How do you experience the vibrations from the ferry itself?	Electric propulsion (%)	Hybrid propulsion (%)
Very small/ Not disturbing	68	68
Quite small/ Slightly disturbing	25	24
Neither or	5	4
Quite large/ Disturbing	0	0
Very large/ Very disturbing	3	0
Have no opinion	0	4



How satisfied are you overall with the onboard comfort in terms of noise and vibrations on this journey?	Electric propulsion (%)	Hybrid propulsion (%)
Very pleased	63	64
Rather pleased	23	28
Neither or	8	8
Rather dissatisfied	0	0
Very dissatisfied	3	0
Have no opinion	5	0

Other aspects reported by the passengers

- The ferries here are very quiet.
- The ferries are good – when they are operational, several people commented.
- Several passengers expressed that there have been a lot of technical issues and canceled trips in the past year.
- "Sometimes you have to wait for half an hour; it doesn't work for those of us who live here".

About the respondents

The majority, 49%, travel with the road ferries several times a week. 17% travel once a week, and another 15% travel a few days per month. 17% travel less frequently.

Most, 44%, are commuters to and from work or studies. 13% travelled for business purposes. 27% took a leisure trip, 3% were tourists and 14% took a different type of trip.

The majority, 34%, were in the age range of 40–59 years. The next largest category, 20-39 years, accounted for 32%. The group between 60-79 years old accounted for 29%. Among those who responded to the survey were 5% 19 years old or younger. No one was 80 years or older.

The survey was answered by more men than women (59% and 35%, respectively). Others chose not to disclose or selected another gender.

The investigators observations

- The investigation was done at low season, during high season there are more tourists.

- There was limited time on board to conduct the questionnaire, there was a window of approximately 7-8 minutes after departure when the passengers had the time or willingness to respond.
- It was generally challenging to get passengers to respond to the survey, especially in the early afternoon on board Neptunus.
- It was easier to get commuters in the afternoon on board Tellus to respond.

D Styrsöbolaget – hybrid vs electrical propulsion on a passenger ferry

D.1 Introduction

The Styrsöbolaget case study was performed in 2022 and 2023. An initial visit to the ship was performed in March 2022. Crew interviews were performed 27-28 April and 5 May 2022, and the passenger surveys 22 Feb 2023. The radiated noise measurements (Table 22) were performed 17 May 2022 together with onboard noise and vibration measurements.

Table 22. Styrsöbolaget radiated noise measurement log.

Time	Propulsion	Distance to hydrophones	Distance to microphones	Included in analysis
14:22	Electric	68 m	98 m	No
14:30	Electric	83 m	96 m	No
14:40	Electric	89 m	91 m	Yes
14:57	Electric	90 m	90 m	Yes
15:06	Electric	93 m	87 m	Yes
15:13	Electric	95 m	84 m	No
15:17	Electric	84 m	84 m	No
15:32	Electric	87 m	93 m	Yes
15:43	Electric	96 m	84 m	Yes
16:05	Electric	91 m	89 m	Yes
16:23	Hybrid	107 m	74 m	No
16:40	Hybrid	97 m	83 m	Yes
16:50	Hybrid	118 m	63 m	Yes
16:58	Hybrid	101 m	77 m	Yes
17:12	Hybrid	113 m	68 m	Yes
17:27	Hybrid	108 m	73 m	No
17:34	Hybrid	88 m	81 m	No
17:41	Hybrid	100 m	79 m	Yes
17:52	Hybrid	97 m	83 m	Yes
17:52	Hybrid	97 m	78 m	No
17:57	Hybrid	103 m	78 m	Yes

The positions of the measurement track and noise sensors are presented in Table 23 below.

Table 23. Positions of measurement track and sensors for the Styrsöbolaget radiated noise measurements.

Position	Coordinates
Measurement track, start	57° 35.510' N 11° 48.138' E
Measurement track, end	57° 35.423' N 11° 48.622' E
SilentRaft	57° 35.523' N 11° 48.424' E
Hydrophones	57°35.424’N 11°48.350’E

Figure 62 presents photos from the Styrsöbolaget study.

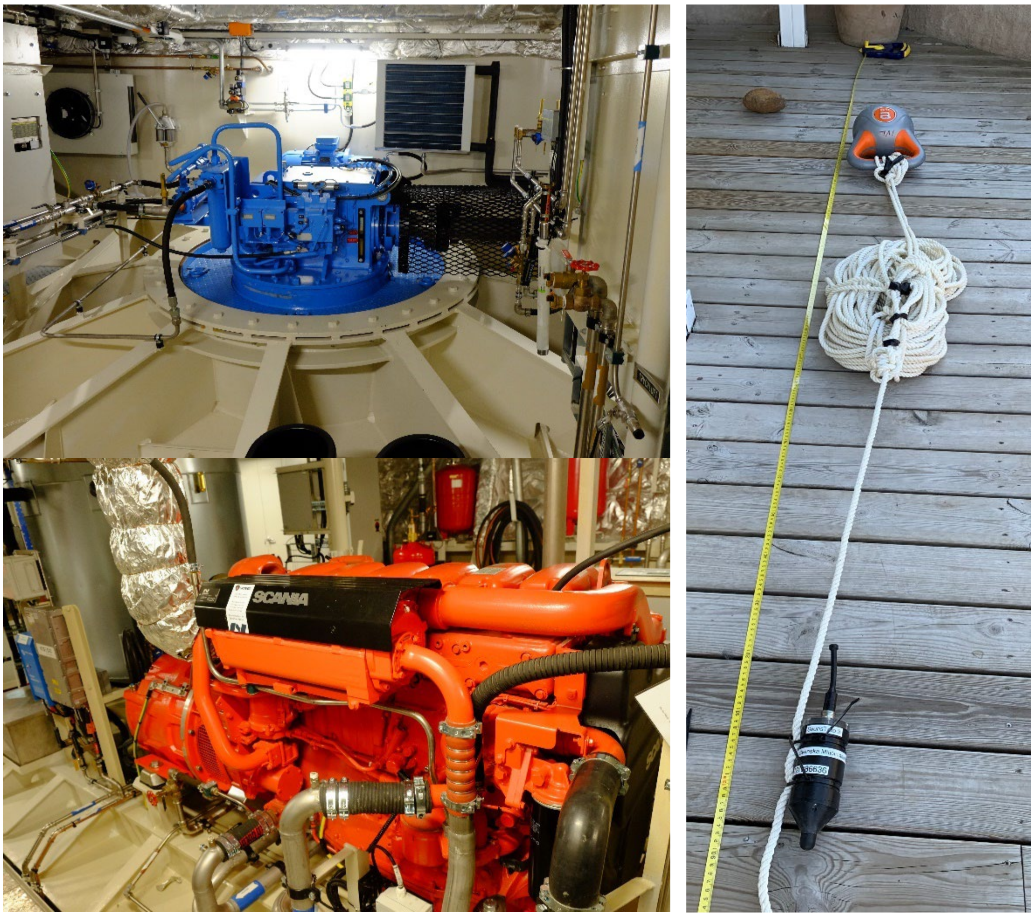


Figure 62. Photos from the Styrsöbolaget study. One of Elvy’s thrusters (top left) and her diesel engine and generator (bottom left). Autonomous hydrophone placed on rope, with weight, before deployment (right).

D.2 Radiated noise

D.2.1 Airborne noise

For Styrsöbolaget the shuttle ferry Elvy was measured in fully electric as well as hybrid mode running a diesel generator that was charging the batteries while under way. As can be seen by the average 1/3 octave band spectra for each mode of propulsion in Figure 63, the main difference between the modes of propulsion can be found in the frequency band at 80 Hz where there is an increase in level of about 12 dB for the hybrid propulsion mode. This corresponds well to what could be expected from a marine diesel of that size.

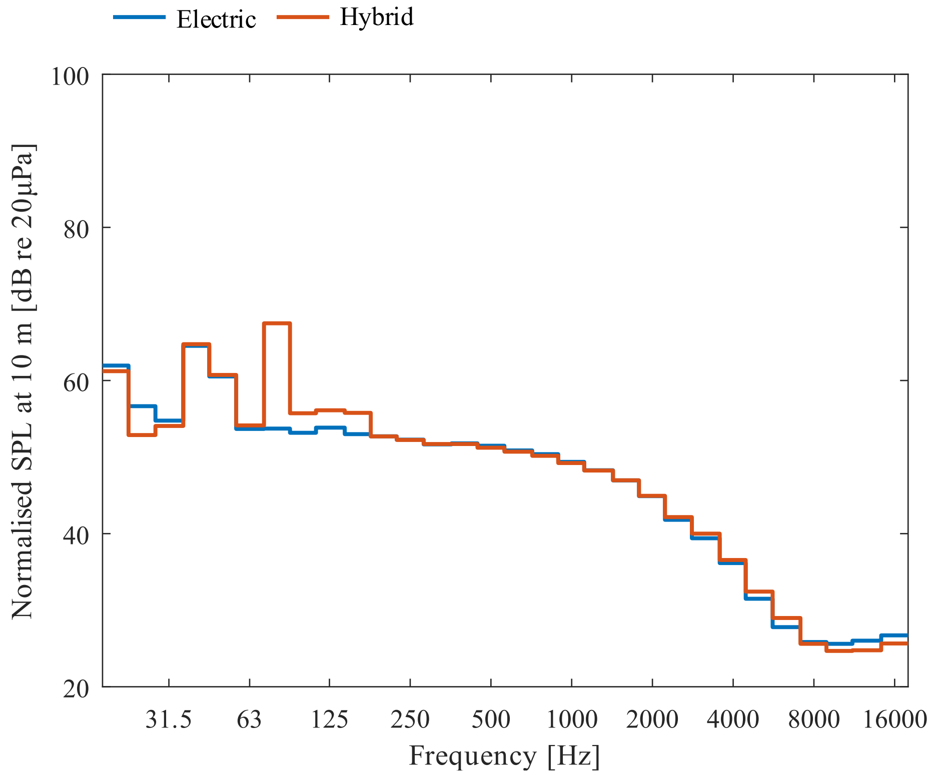


Figure 63. 1/3 octave band spectra of airborne noise from Elvy under electric and hybrid propulsion modes.

D.2.2 Underwater noise

The underwater radiated noise measured from Elvy is shown in Figure 64. At lower frequencies, below 2 kHz, the spread of the measured levels is low around 3 dB. At higher frequencies the spread is much larger, with the hybrid case having an average spread of 9 dB. Overall, the measured level is quite low, well below the reference curve from the BV method. However, this curve is designed for much larger ships, so it is expected that Elvy is quieter.

Looking at the differences with the onboard diesel generator running (hybrid mode) and turned off (electric mode), there is a clear difference in level for the 125 Hz band and the 160 Hz band. The differences in these bands are 10 dB and 9 dB respectively. This is clearly the contribution of the diesel generator, since it is the only difference in the state of the ship between the measurements.

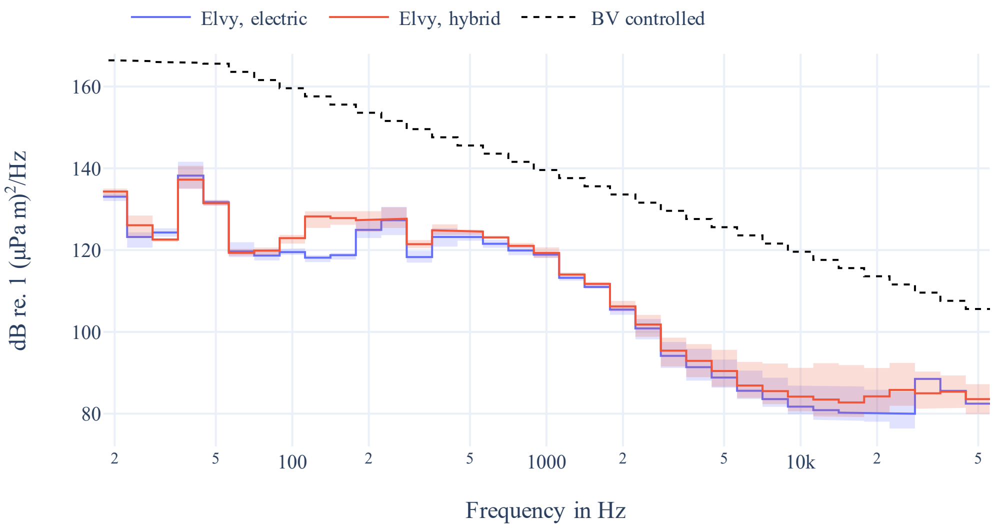


Figure 64. Underwater radiated noise from Elvy, in electrict and hybrid mode. The shading indicate the largest spread of noise levels between measured passages.

D.2.3 Noise sources

The received noise level measured for Elvy is shown with high frequency resolution in Figure 65, with results in air and in water in the two rows, and the electric and hybrid cases as two lines in each axis. The groupings of identified tones are also shown in these figures, by coloring each peak with the corresponding color. The most apparent result are the very distinct tones from the diesel generator, that appear only in the hybrid operating mode. Elvy has a six-cylinder four-stroke diesel engine operating at 1600 RPM, which corresponds to a 26.6 Hz. There is a strong component in air at 80 Hz, which is the third-order harmonic to the rotation speed. This is expected since there are three ignitions per revolution in the engine. There is also a strong airborne component at 40 Hz, which could potentially be due to asymmetry in the diesel cylinders. At higher frequencies, centered around 145 Hz, a series of harmonics can be seen with a spacing of

13.3 Hz, in both air and water. These harmonics are of quite high orders, around 6 to 15 times the fundamental frequency of 13.3 Hz. In the other case studies in the project, such high harmonics were not seen from the diesel engine itself. It could be the case that the noise originates at some machine connected to the diesel engine via gearing. The three harmonic cluster in air hint at a machine with a gearing ratio of 2:11 (the central of the three), which is then modulated by the generator shaft rotation. This corresponds to a very fast operating speed of 8800 RPM, but the machine could also be further geared down, if the noise stems from the gears themselves.

The propeller is driven by an electrical engine operating at 1000 RPM during the measurements. This drives the propellers through a 3.5 times step-down gearbox, giving a propeller speed at around 285 RPM. The propeller design is a 4-blade duo prop, which makes the blade passing frequency for each propeller 19 Hz. This tone can be seen clearly both in air and water, like in the other case studies in the project. The airborne noise is likely transmitted via pressure pulses from the propeller that excite the hull, then radiating from the hull into the air.

In addition to the components from the diesel generator and the propeller, there are two tones at 43.2 Hz and 48 Hz that to not match harmonics of the propeller, generator, or electrical engines. Since the trials were only performed at a single speed, it is difficult to determine if these tones are related to the propulsion or not. However, the lower of the two tones is at a 2:5 ratio from the engine speed, while the upper of the two tones is at a 7:20 ratio from the engine speed (or 1:10 to the propeller rotation).

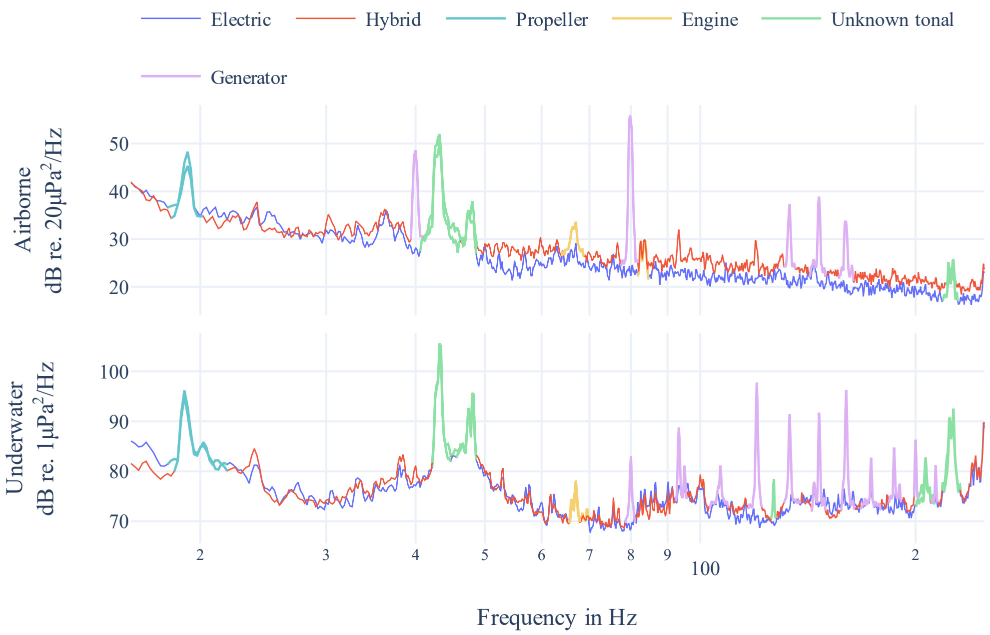


Figure 65. Identified tones for Elvy.

The share of noise power from each identified source is shown in Figure 66. As for the other cases studied, the generator contributes roughly 50 % of the airborne noise in hybrid mode. The underwater noise is mostly caused by the above-mentioned unidentified tones, particularly in the electric mode. This highlights the importance of understanding the mechanical design when doing measurements, and how much noise can be generated by unexpected sources on a ship.

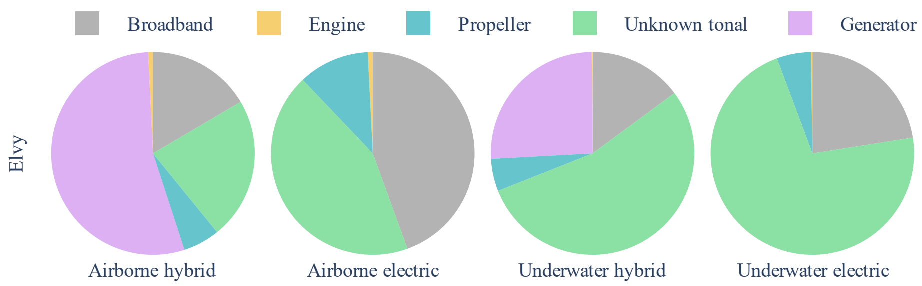


Figure 66. Noise power distribution for Elvy.

D.3 Onboard noise

The onboard noise was measured in close connection to the underwater and air borne (outdoor) noise but not exactly at the same time.

A handheld class 1 sound level meter, Svantek 957, was used to record and analyze the sound level. A manual sweep was used to get a spatial average of the sound in the measured rooms. No corner position was used. Due to a technical problem, it was only possible to retrieve the total A-weighted levels from these measurements, not the spectrum.

A list of the measured rooms and their equivalent A-weighted results are found in Table 24.

Table 24. Onboard measured A-weighted sound pressure levels in different rooms onboard Elvy for her two propulsion cases, hybrid and electric.

Elvy	Hybrid L_{Aeq} (dB)	Electric L_{Aeq} (dB)
Engine room (stern)	86	83
Engine room (middle)	103	62
Passenger deck side	60	54
Passenger deck middle	70	55
Middle zone	55	48
Bridge	51	53

D.4 Work and passenger environment

D.4.1 Work environment

Six interviews were conducted either via Teams or on site. The interviewees had varying length of experiences.

The content of the interviews is summarized in the following. We have focused on the essence of the answers. The interviewees wordings are here simplified and translated to English.

Summary

- Elvy is generally perceived as quieter than the older vessels.
- There is a general positive experience of the work environment.
- The electrical propulsion has some special features including new noise generations.

- Suggestions of improvements concern the heating onboard and work shoes which reduces the exposure of vibrations.
- The interviewees ask for more knowledge about how to handle risks with the electrical propulsion, batteries and fire safety.

Perception of the work environment with respect to noise and vibrations

The experiences of noise and vibrations align with the results from (previously) conducted measurements on board.	It is quieter with fewer vibrations than on any boat I have ever been on. The most disappointing aspect of the working environment on this boat is that it has such large spaces, but there are no crew spaces. Modern boats with control systems, heating systems, and more take up so much space.	Positive experience: it is quiet, which is pleasant. You think more clearly, and reduced fatigue is noted.
Where the battery is located, the inverter makes a whistling sound, and there is noise (a hum) when the battery is charged with a diesel generator, approximately 45 minutes, 4-5 times a day.	Deckhands can feel vibrations when turning the pod and accelerating, for example, during mooring and also in waves in the river when the hull absorbs the shocks.	Initially unusual not to hear engine sounds, for example, during manoeuvring, arrival, and departure, when changes in RPM used to be audible.
On the bridge, the main sound is the fan noise from the ventilation.	Fantastic environment. People can communicate with each other in the engine room.	There are seldom alarms on Elvy.

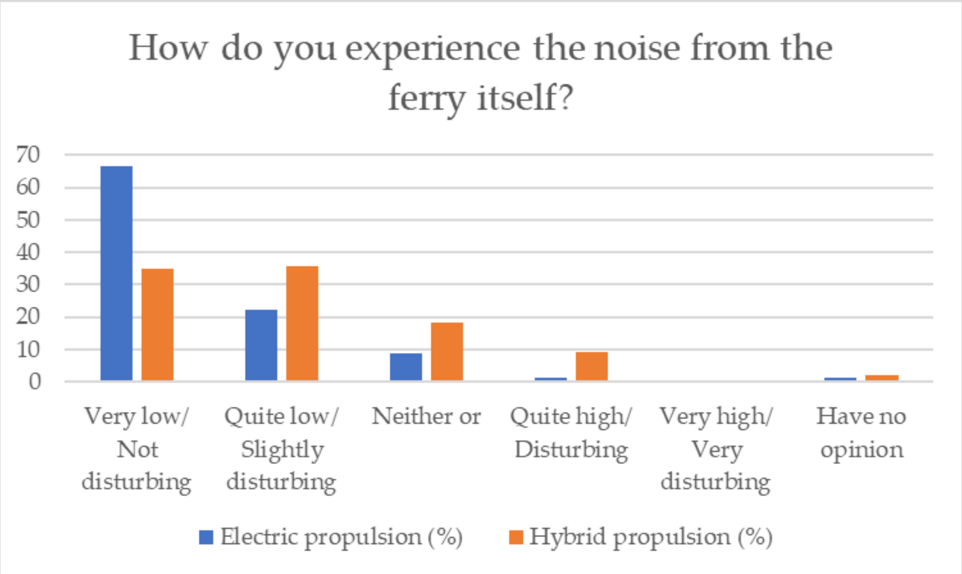
D.4.2 Passenger environment

During the investigation onboard Elvy, the deckhand notified the Silent@Sea investigator which propulsion mode was active for the specific passage and the corresponding QR-code was then provided to the passengers. In this way it was possible to separate the answers from the two modes. During electrical propulsion 220 persons answered the questionnaire, compared with the hybrid mode where 99 persons answered, in total 319.

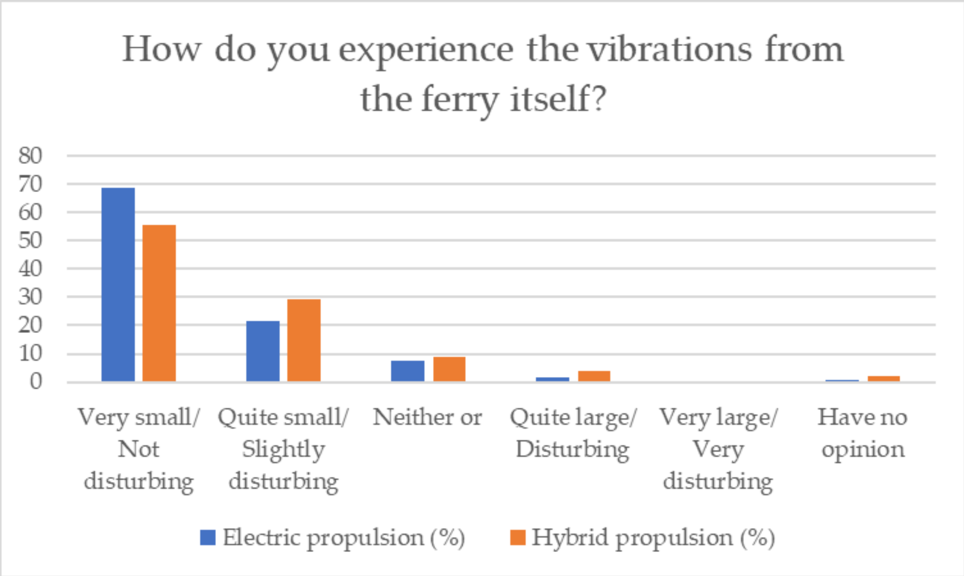
Summary

The absolute majority of passengers are not disturbed by the ferry's noise and vibrations, regardless of propulsion mode. Still the results show that the passengers' experience of noise and vibrations on board differs between electric and hybrid propulsion with more people being very pleased and not disturbed by noise and vibrations during the electric propulsion.

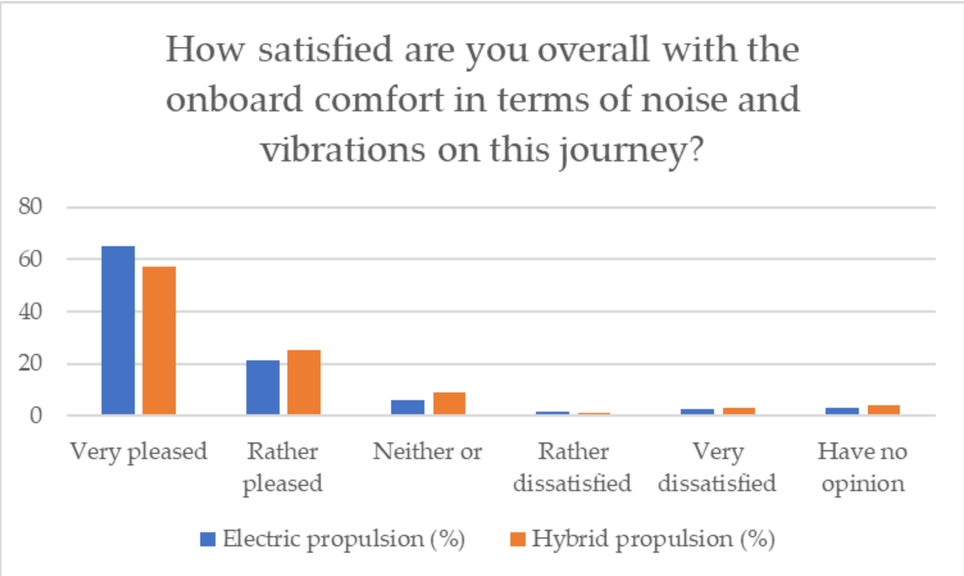
Questionnaire results



How do you experience the noise from the ferry itself?	Electric propulsion (%)	Hybrid propulsion (%)
Very low/ Not disturbing	66	35
Quite low/ Slightly disturbing	22	36
Neither or	9	18
Quite high/ Disturbing	1	9
Very high/ Very disturbing	0	0
Have no opinion	1	2



How do you experience the vibrations from the ferry itself?	Electric propulsion (%)	Hybrid propulsion (%)
Very small/ Not disturbing	69	56
Quite small/ Slightly disturbing	21	29
Neither or	7	9
Quite large/ Disturbing	2	4
Very large/ Very disturbing	0	0
Have no opinion	1	2



How satisfied are you overall with the onboard comfort in terms of noise and vibrations on this journey?	Electric propulsion (%)	Hybrid propulsion (%)
Very pleased	65	57
Rather pleased	21	26
Neither or	6	9
Rather dissatisfied	2	1
Very dissatisfied	3	3
Have no opinion	3	4

Other aspects reported by the passengers

- The chairs are very cold
- The sounds of other people's conversations can be disturbing, more than the noises from the ferry itself.
- It is good that the journey is free of charge.

About the respondents

The majority, 70%, travel with the ferries across the Göta Älv several times a week. 11% travel once a week, and another 11% travel a few days per month. 7% travel less frequently.

Most, 78%, are commuters to and from work or studies. 5% travelled for business purposes. 13% took a leisure trip, and 3% took a different type of trip, such as a shopping trip to the city.

The majority, 46%, were in the age range of 20-39 years. The next largest category, 40-59 years, accounted for 31%. Approximately the same number were under 19 years old as between 60-79 years old (13% each). Among those who responded to the survey, 0.3% were 80 years or older.

The survey was answered by slightly more men than women (50% and 47%, respectively). Others chose not to disclose or selected another gender.

The investigators observations

- Many thought that Elvy is fully electric.
- Elvy was perceived as quiet even during charging with diesel operation.
- Some commented during diesel operation that it is quiet, but even quieter with electric.
- More men than women commute to and from Lindholmen.

- There were many young people who traveled and only a few in the oldest age group.
- The passengers were very accommodating, and most answered the survey.
- Several non-Swedish passengers could not participate even if they wanted to because the questionnaire was only available in Swedish.

E Furetank – diesel vs LNG propulsion on tanker vessels

E.1 Introduction

The Furetank case study was performed in 2023. An initial visit to the ships was performed 17 March 2023. Crew interviews were performed 17 March 2023. The radiated noise measurements (Table 25) were performed 5 April 2023 to 20 May 2023. Onboard noise and vibration measurements were performed 18 to 20 March 2023.

Table 25. Furetank radiated noise measurement log.

Time	Vessel	Condition	Speed (kn)	Range	Direction
29/4, 08:55	Fure Vinga	Diesel, ballast	10.9	138	East
1/5, 03:14	Fure Vinga	Diesel, laden	11.8	251	West
20/4, 13:58	Ramanda	Diesel	11.7	172	East
14/4, 21:59	Fure West	Diesel	13.1	280	West
15/4, 02:44	Ramona	Diesel	12.7	297	West
1/5, 19:12	Ramona	Diesel	12.7	278	West
11/5, 16:41	Ramona	Diesel	14.9	297	West

The positions of the noise sensors are presented in Table 26 below. There was no specific measurement track for Furetank; the ships followed their normal routes within the fairway.

Table 26. Positions of sensors for the Furetank radiated noise measurements.

Position	Coordinates
Microphones	57° 38.958' N 11° 43.186' E
Hydrophone	57° 38.994’ N 11° 43.235’ E

Figure 67 presents photos from the Furetank study.

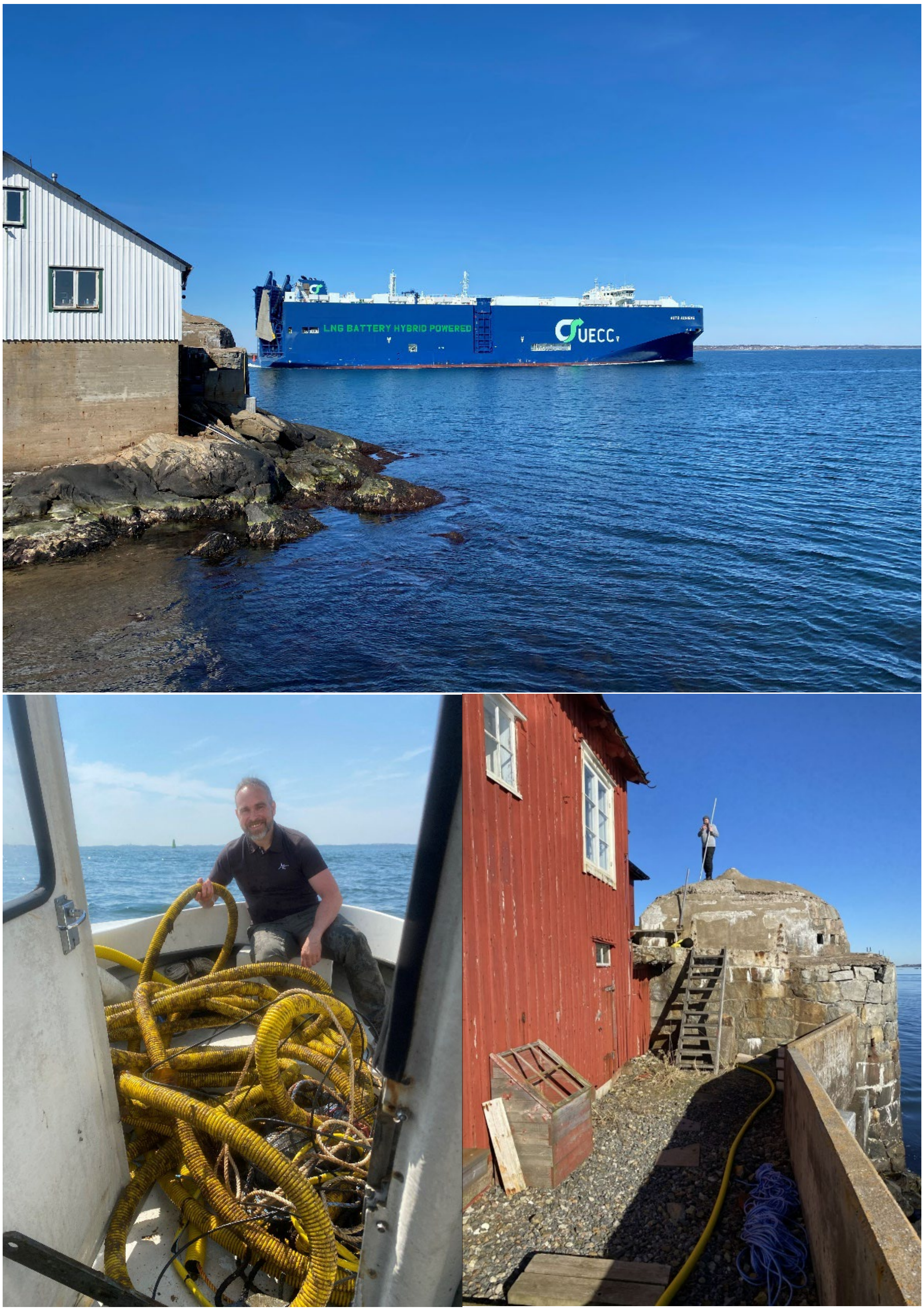


Figure 67. Photos from the Furetank study. A ship passing the measurement site (top), the underwater equipment after recovery (bottom left) and setting up the microphones (bottom right).

E.2 Radiated noise

E.2.1 Airborne noise

As mentioned, for Furetank the data ended up being of such low signal to (wind) noise ratio as to be very unreliable. Figure 68 shows an example of a passage of the tanker Ramona where the airborne signal is dominated by wind noise and does not vary when the vessel passes, as compared to the hydrophone signal showing a prominent peak near the closest point of approach. Only three passages provided low enough wind speeds to reduce intrusive noise, but there seemed to be other traffic nearby making the isolation of noise from a specific ship unreliable.

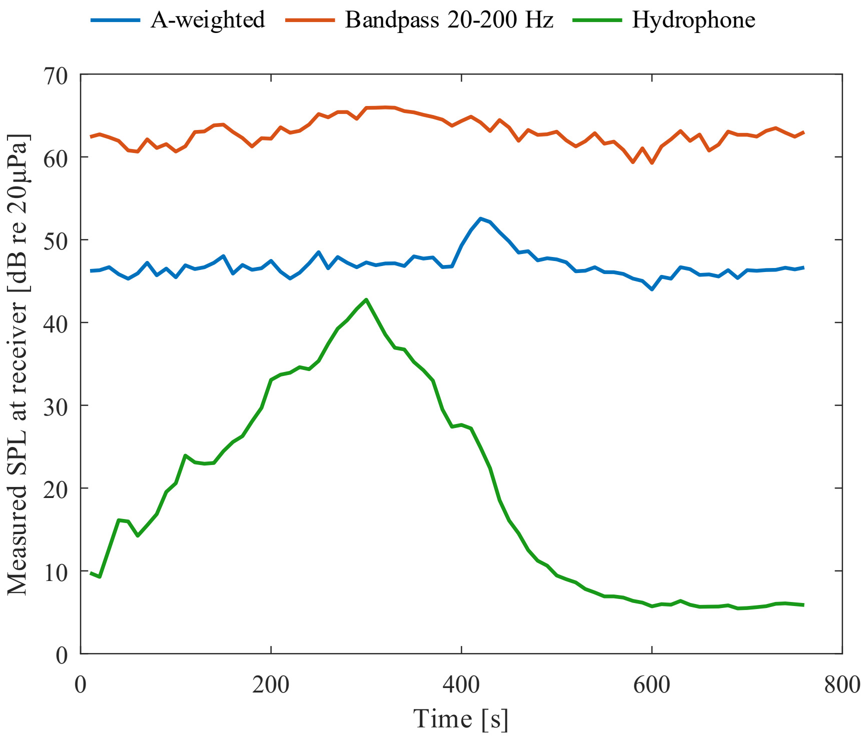


Figure 68. Momentary sound pressure level over time during a passage of the tanker Ramona. The hydrophone levels are not calibrated but are included for comparison of SNR. Blue curve is a-weighted level, red curve represents the signal band pass filtered 20-200 Hz.

E.2.2 Underwater noise

During the deployment of the measurement station a number of passages were measured, both from ships owned by Furetank but also similar sister ships owned by other members of the Gothia Tanker Alliance. The analysis here only includes passages where there was sufficient distance to other commercial ships in the area, to only capture the radiated noise from the measured ship.

The underwater radiated noise from the ships Fure WEST (2006) and Ramona (2004) is shown in Figure 69, with three passages from Ramona and a single passage from Fure WEST. There is a much larger spread between these measurements, which is expected since the passages were performed with much less control over environmental conditions and more variations in the onboard conditions. Similarly, the underwater radiated noise from Fure Vinga (2021) and Ramanda (2018) is shown in Figure 70, with a similar spread amongst the passages. Comparing the two groups, see Figure 71, there is a tendency that the newer ships are quieter than the older ships by an average of 8 dB. For context, to achieve an 8 dB decrease with a reduction of the number of ships it would be necessary to remove 85% of the passing ships.

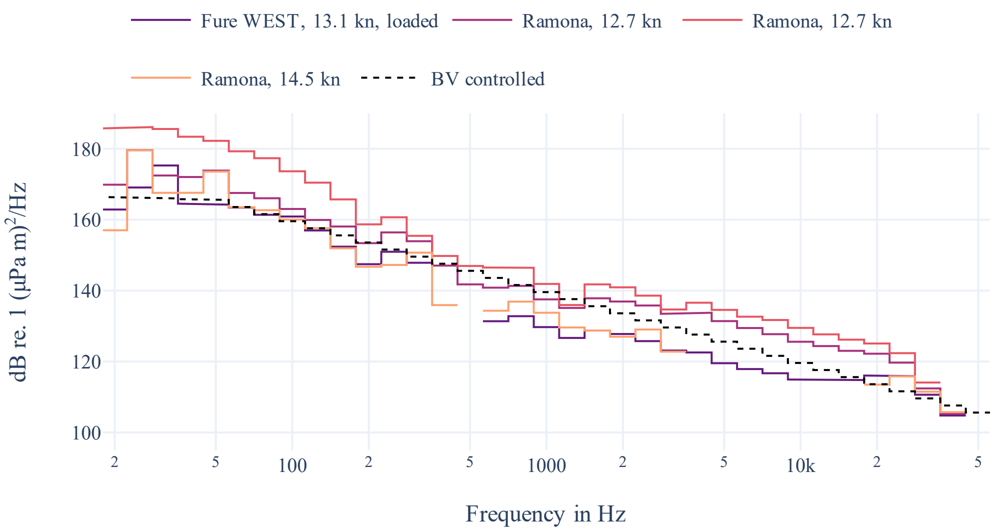


Figure 69. Underwater radiated noise from the older Furetank vessels. Gaps indicate frequencies where the recorded signal was not sufficiently above the background noise.

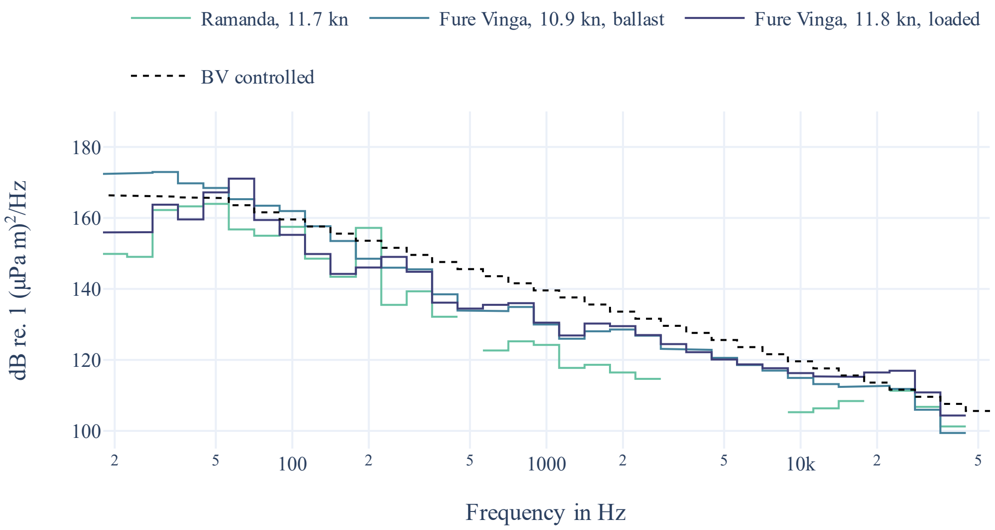


Figure 70. Underwater radiated noise from the newer Furetank vessels. Gaps indicate frequencies where the recorded signal was not sufficiently above the background noise.

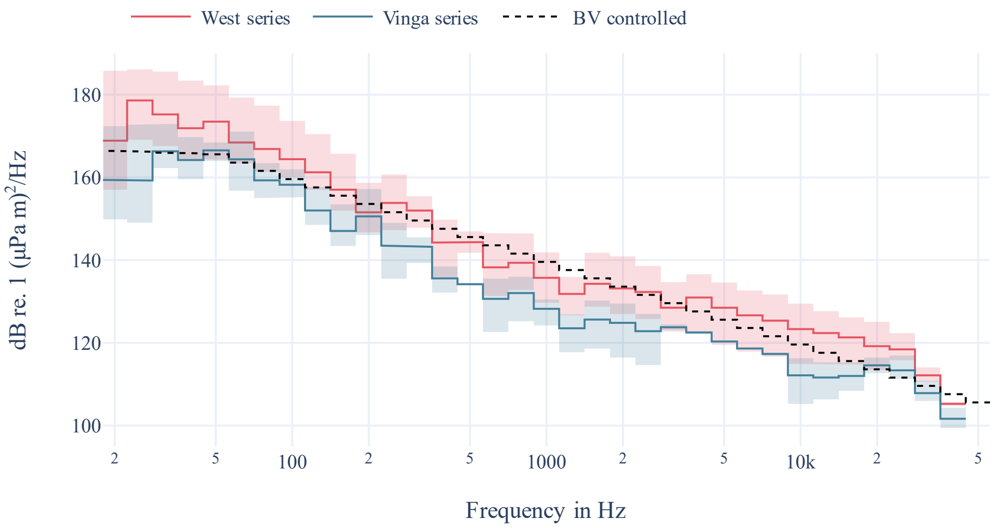


Figure 71. Comparison between radiated underwater noise from older (West series) and newer (Vinga series) Furetank vessels. The shading indicates the highest and lowest levels measured in each class.

E.2.3 Noise sources

Noise source identification was not performed for Furetank due to insufficient information on operating conditions.

E.3 Onboard noise

The onboard noise was measured by the staff themselves on the 19th and 20th of March 2023. They placed a sound level meter in different rooms which continuously measured the sound pressure level in one room position for a relatively long period (Svantek 104). Which propulsion mode was active at different times was noted in a log which was later used in the analysis to get an estimate of the difference.

A list of the measured rooms and their equivalent A-weighted results are found in Table 27. The spectra of the measurements can be found in Figure 72–Figure 75.

Table 27. Onboard measured A-weighted sound pressure levels in different rooms onboard Fure Viten for her two propulsion cases, diesel and LNG.

Fure Viten	Diesel L_{Aeq} (dB)	LNG L_{Aeq} (dB)
Engine room	105	102
Engine control room	68	67
Cabin	60	60
Bridge	61	60

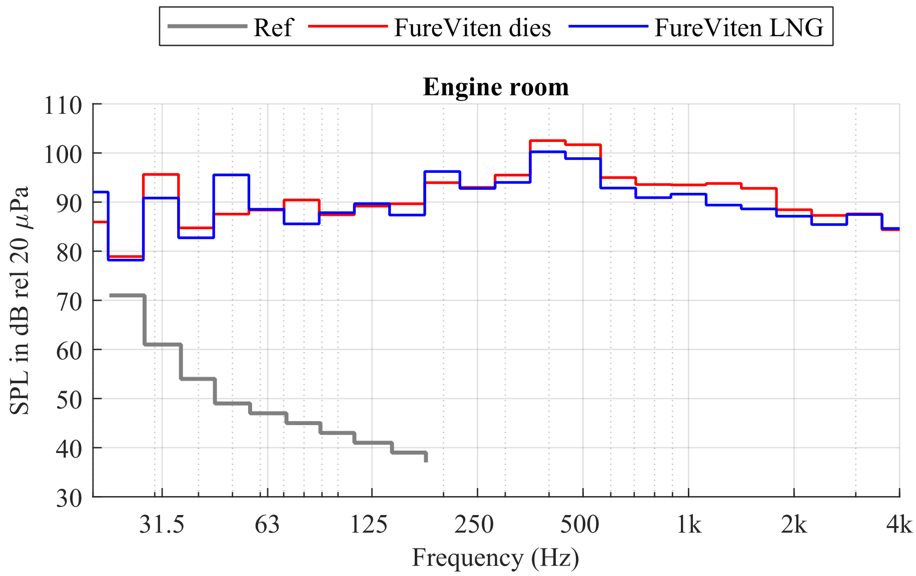


Figure 72. Onboard measured sound pressure levels in decidecade (1/3 octave) band levels in the engine room. The "Ref" curve can be used as guidance when assessing the risk for disruption of low-frequency noise for working conditions with high demands on continuous concentration according to the Swedish Work Environment Authority.

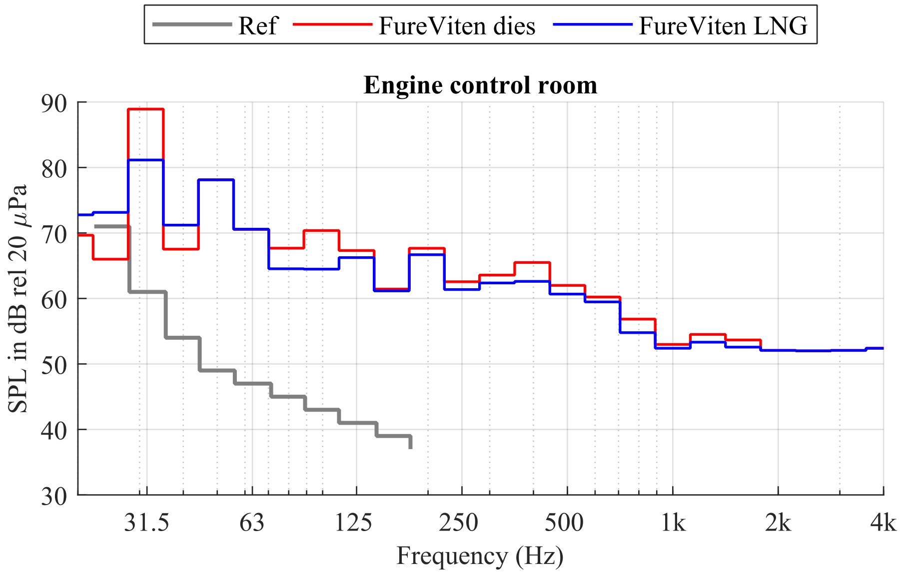


Figure 73. Onboard measured sound pressure levels in decidecade (1/3 octave) band levels in the engine control room. The "Ref" curve can be used as guidance when assessing the risk for disruption of low-frequency noise for working conditions with high demands on continuous concentration according to the Swedish Work Environment Authority.

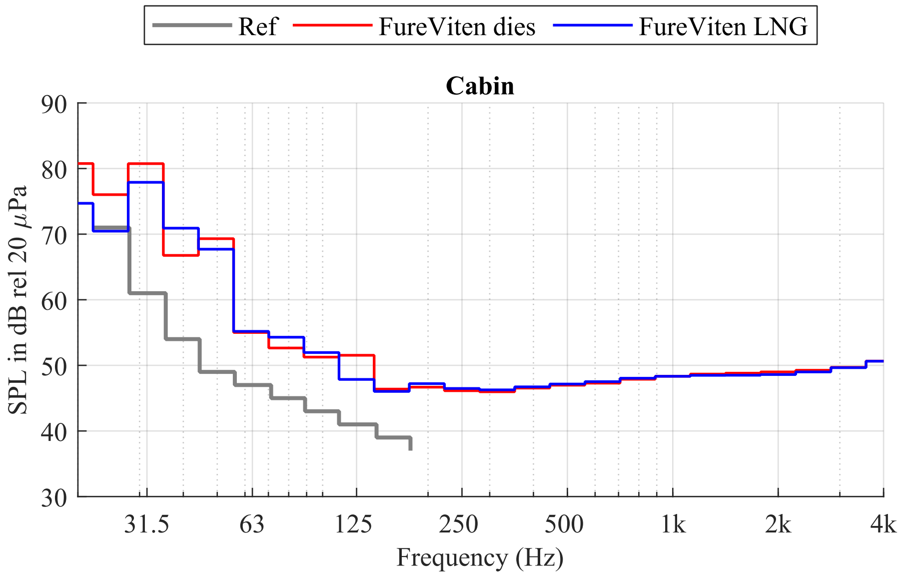


Figure 74. Onboard measured sound pressure levels in decidecade (1/3 octave) band levels in a crew cabin. The "Ref" curve can be used as guidance when assessing the risk for disruption of low-frequency noise for working conditions with high demands on continuous concentration according to the Swedish Work Environment Authority.

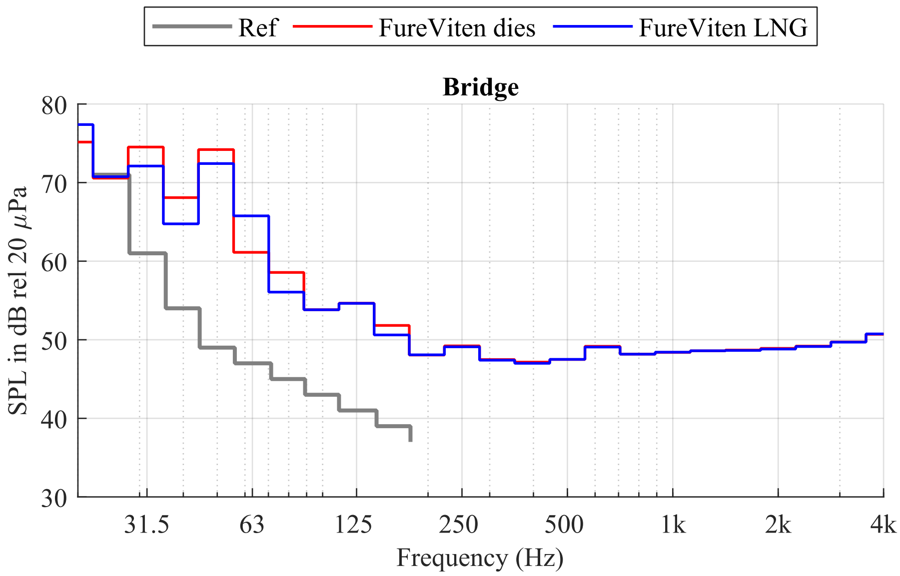


Figure 75. Onboard measured sound pressure levels in decidecade (1/3 octave) band levels on the bridge. The "Ref" curve can be used as guidance when assessing the risk for disruption of low-frequency noise for working conditions with high demands on continuous concentration according to the Swedish Work Environment Authority.

E.4 Work environment

Four interviews were conducted onboard Fure Viten. There was a mix of onboard responsibilities among the interviewees including deck and machinery and a variation in age, gender and experience and nationality.

The contents of the interviews are summarized in the following. We have focused on the essence of the answers. The interviewees wordings are here simplified and translated to English.

Summary

- Everyone agrees that the working environment on board is very good.
- Overall, Fure Viten is quieter compared to older ships.
- LNG propulsion is quieter, especially in the engine room and control room.
- Otherwise, it is the ventilation noise that is mainly heard, especially in cabins where it can be disturbing when trying to sleep.
- Noise comes from people moving around from ladders and doors and it can disturb sleep.
- Several people are disturbed by alarms while sleeping. Even those who are not on duty hear alarms.

- There are vibrations, but they don't bother anyone. Poor weather conditions, in particular, lead to more vibrations.
- No noise and vibration risks were identified. However, there are chemical risks, freezing risks, ship movements in bad weather, risks with ropes and winches, but there are procedures for everything.
- Improvements mentioned include quieter ventilation in cabins and adjustments for female personnel.

Perception of the work environment with respect to noise and vibrations

There is a difference between diesel and LNG. LNG is quieter in terms of sound.	In the cabin, it is not possible to completely reduce the fan noise. You can lower it, and then it becomes quite quiet.	Alarm noise from the engine can be disturbing in cabins; it has happened on an older sister ship.
Alarms come from equipment and on the radio. Not as much as in the beginning, there are fewer alarms now.	I haven't experienced any sound difference between LNG and diesel. During the transition, the shift from LNG to diesel produces a sound ("puff").	On deck, fans from the main engine can be heard. The wind blows so much on deck that the radio cannot be heard.
Quieter, smoother, good design.	The ship is better than conventional vessels.	Fure Viten is a very clean boat environmentally and in terms of noise.
LNG is better than diesel. A very well-optimized vessel. Optimized hull, propeller. The concept is very successful.	The engine room is quiet. It is only noisy in the engine room. Cannot determine which fuel is used when outside the engine room.	Vibrations exist on ships. Not so disturbing that it affects work. Vibrates less and less higher up in the boat.
Very good regarding noise.	Can hear faint noise at sea from the main engine. Some creaking, small sounds.	The radio is always on.

There is always someone on board who is on duty and receives alarms. The second/first engineer can receive alarms all the time. Disturbing for the cabins nearby.	General experience is that it is quiet on board. Haven't thought about the noise, not bothered. So quiet that the ventilation is the most noticeable, both in port and at sea.	Even when running on diesel, there is clearly less noise compared to older ships.
Initially thought the engine wasn't running because it was so quiet. Completely silent on the boat with LNG.	The most significant vibrations occur at a constant speed, and they only have that when manoeuvring. Large movements are made, and it can cause vibrations.	Vibrations depend on the weather. Approximately the same vibrations with LNG and diesel operation.
The engine room is significantly quieter with LNG. Nothing can be heard in the control room with LNG.	Much quieter in the engine room with LNG propulsion compared to diesel.	

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This report has been reviewed and approved in accordance with IVL's audit and approval management system.

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