Ultrasonic antifouling system for preventing marine growth onboard ships

Initial evaluation of efficacy and environmental side effects

Final report

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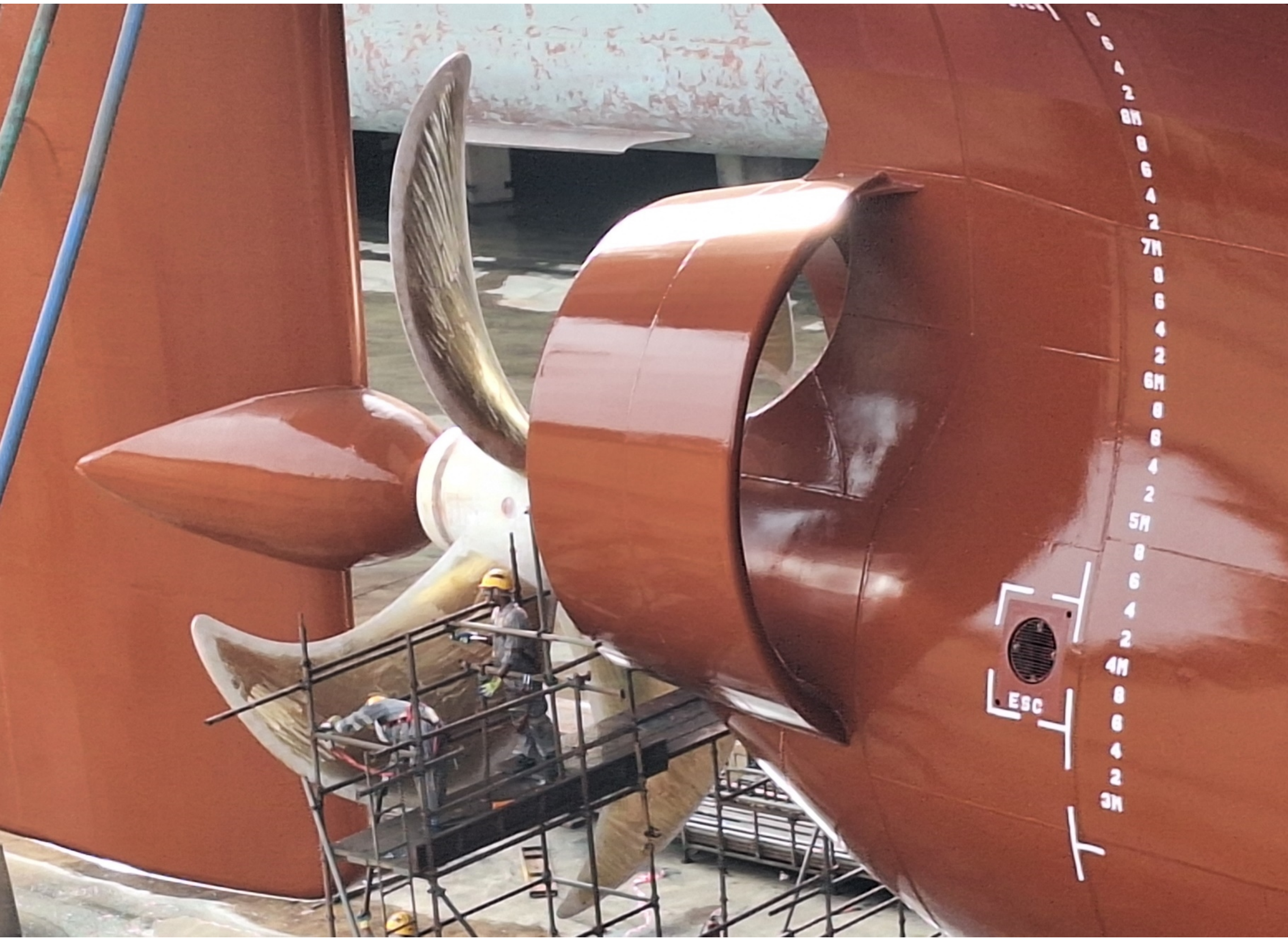
Prepared for The Danish Maritime Fund



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Prepared for: The Danish Maritime Fund

Approved by
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Contact person: Torben Madsen, tma@dhigroup.com
Authors: Torben Madsen, Pernille Bohn, Esperanza Mary Rose, Matthias Ram

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DHI A/S • Agern Allé 5 • DK-2970 Hørsholm • Denmark
Telephone: +45 4516 9200 • dhi@dhigroup.com • www.dhigroup.com • Company Reg. No.: DK36466871

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Definitions

Term	Definition
Auditory injury (AUD INJ)	Auditory injury to marine animals is associated with damage to the inner ear which may or may not result in a permanent threshold shift (PTS). PTS is a permanent hearing impairment, i.e., an irreversible increase in the threshold of an individual's capability of hearing or perceiving sounds at a certain frequency.
Biofouling	Biofouling (or simply fouling) is the gradual accumulation of microorganisms, algae or invertebrates on surfaces exposed to water, such as vessel hulls and the vessel's seawater cooling system.
Cetaceans	Cetaceans are aquatic mammals that belong to the order Cetacea, which includes whales, dolphins, and porpoises.
Noise	Sound that is not a useful signal and has no biological function in the environment. Noise may either be neutral or may have adverse effects on marine life.
1/3 Octave band	Interval of 1/3 of an octave. Three adjacent 1/3 octave bands span one octave.
Root mean square (RMS)	Root mean square is a statistical measure, which may be used to calculate an average that accounts for fluctuating data.
Sound	The acoustic energy radiated from a vibrating object with no reference to its function or potential effect.
Sound exposure level (SEL)	The sound exposure level is a measure of the amount of sound energy received integrated along a specific time interval and is commonly used to establish noise level thresholds.
Cumulative sound exposure level (SEL_{cum})	Cumulative sound exposure level over 24 hours.
Sound pressure level (SPL)	Sound pressure level [dB re 1µPa] – sound pressure expressed in decibels [dB] relative to a reference pressure P_{ref}=1µPa.
Temporary threshold shift (TTS)	Temporary threshold shift in marine animals is a temporary hearing impairment, i.e., a reversible increase in the threshold of an individual's capability of hearing or perceiving sounds at a certain frequency.
Underwater radiated noise (URN)	Underwater radiated noise, or simply underwater noise, refers to the sound energy emitted under water, frequently originating form ships, sonar systems, and industrial activities (see also 'Noise').

Executive summary

Biofouling of vessels leads to higher fuel consumption and operational costs and increases greenhouse gas emissions. In addition, ship's biofouling is a source of non-indigenous species, which after transfer to areas outside their natural range might become invasive and thus be a threat to biodiversity

An ultrasonic antifouling system produces high-frequency sound waves that create a micro-vibrational field in the metal structures of the vessel which affects the attachment of fouling organisms. In this study, ultrasonic antifouling transducers were installed in the entire seawater cooling system, around the propeller shaft, and on the inside of the hull near the propeller shaft of the crude oil tanker HAFNIA GALATEA and on the inside of the hull of the diving vessel EARL 3. Furthermore, the efficacy of the ultrasonic antifouling system was examined by evaluation of the fouling on steel panels in a harbour in South Fremantle, Perth, Western Australia.

The ultrasonic antifouling system onboard HAFNIA GALATEA showed variable efficacy in its capability to prevent marine growth. The ultrasonic transducers apparently helped reducing the fouling of the sea chest strainer, the central freshwater cooler, and the air ejector condenser, while no such effect was seen for the vacuum condenser and the propeller blades. Furthermore, bivalve shells captured on the low-temperature (LT) cooler filter mesh indicate that the fouling protection of the piping leading to the LT cooler filters was insufficient. Promising effects of the ultrasonic treatment were thus indicated in parts of the seawater cooling system onboard HAFNIA GALATEA, but a proper evaluation of the potential of the ultrasonic antifouling system requires a longer time span allowing optimization of the transducer installations and deeper understanding of the fouling pressure of the ambient water encountered along the vessel's travel route.

Clear evidence of the potential of the ultrasonic antifouling system to prevent marine fouling was provided in the harbour test in Western Australia. When ultrasonic transducers were mounted on submersed steel panels for 69 days, the ultrasonic treatment kept the surface clean of fouling, while the control panel was virtually overgrown with macrofouling.

The underwater radiated noise emitted from the ultrasonic transducers onboard HAFNIA GALATEA and EARL 3 was measured in the Singapore Strait. The sound measurements were used as input to sound propagation models for the Singapore Strait and the Skagerrak which is a strait between the Jutland peninsula of Denmark, the east coast of Norway and the west coast of Sweden. The predicted propagation of the underwater noise was used to assess the potential adverse effects of the noise on marine mammals represented by a group of whales known as cetaceans. These whales are known to be sensitive to sound in the relevant wavelengths and can be divided into low-frequency cetaceans (e.g., humpback whale), high-frequency cetaceans (e.g., killer whale), and very high-frequency cetaceans (e.g., harbour porpoise) based on their hearing ability.

The immediately received sound pressure emitted from the ultrasonic antifouling system may affect the behaviour of cetaceans within a considerable distance from the sound source. Behavioural reactions to the underwater noise emitted from the ultrasonic transducers onboard HAFNIA GALATEA may occur within ranges of up to 3200 meters for harbour porpoise and within 230 to 410 meters, dependent on

location, for low-frequency- and high-frequency cetaceans. More severe hearing impacts like temporary threshold shift and auditory injury depend on the duration of the exposure to the underwater noise. Assuming that both the vessel and the marine animal are static, a 15-minutes exposure to noise from the ultrasonic antifouling system onboard HAFNIA GALATEA may lead to effects on very high-frequency cetaceans. For example, for very high-frequency cetaceans, temporary threshold shifts caused by noise from the ultrasonic transducers onboard HAFNIA GALATEA may occur within ranges of 905 to 1040 meters, while auditory injury may occur within 80 to 90 meters. It may reasonably be assumed, however, that marine mammals will normally escape when exposed to harmful underwater noise and avoid severe hearing impacts.

This initial evaluation indicates a need for more practical experience with the installation of ultrasonic transducers onboard ships to elucidate the potential of ultrasonic antifouling systems to prevent marine growth. Furthermore, the results indicate that underwater radiated noise emitted from ultrasonic antifouling systems may cause adverse effects on the behaviour and hearing ability of cetaceans and other marine mammals that can hear the sound emitted by ultrasonic transducers. Very high-frequency cetaceans such as harbour porpoise are exceptionally sensitive to the type of noise emitted from the ultrasonic antifouling system examined in the present study. To reduce the adverse environmental effects of underwater noise, the shipping industry may consider route planning avoiding feeding or breeding areas for marine mammals (particularly harbour porpoise), habitats populated with endangered species, and other protected or sensitive sea areas.

The study was funded by a grant from the Danish Maritime Fund.

1 Introduction

Greenhouse gas (GHG) emissions of shipping, including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), expressed as CO_2 equivalents, have increased from 977 million tonnes in 2012 to 1,076 million tonnes in 2018. The total emissions from shipping contribute by approx. 3% of the global emissions of greenhouse gases (IMO, 2021).

Biofouling, or simply fouling, of vessels leads to corrosion and increased water resistance and fuel consumption. Higher fuel consumption leads to increased GHG emissions and counters the IMO ambition to reduce the emissions of international shipping by at least 40% by 2030, moving towards 70% by 2050, compared to 2008. In addition, ship's biofouling is a source of non-indigenous species, which after transfer to areas outside their natural range might become invasive and thus be a threat to biodiversity.

One of the most significant factors impacting fuel efficiency and the GHG emission of vessels is the friction of the hull. The friction of a hull increases with the fouling level, and a clean hull free of fouling is highly important to optimize the energy efficiency of ships. A report published by the GloFouling Partnership describes the dramatic impact of fouling, and, e.g., a layer of slime as thin as 0.5 mm covering 50% of a hull surface may potentially increase GHG emissions by 25 to 30%. More progressed fouling, such as a light layer of small calcareous growth may increase the GHG emissions by up to 60% for an average-length container vessel, and for medium calcareous fouling the increase could reach 90% (IMO, 2022). Biofouling in the internal seawater cooling system is also a challenge, as it can cause blockages of the piping and reduce the heat transfer efficiency, which leads to increased energy consumption and higher operating costs.

Antifouling paint is normally applied to the hull and the propeller when the vessel is in dry dock with the purpose of decreasing the attachment and growth of aquatic organisms. The fouling of the hull and propeller between dockings can be managed by in-water cleaning, e.g., by use of brushes or water jets (BIMCO, 2021). The seawater cooling system is normally protected by the impressed current cathodic protection system preventing corrosion of metal structures and a marine growth prevention system consisting of aluminium and copper anodes preventing corrosion and marine fouling, respectively.

An ultrasonic antifouling system produces high-frequency sound waves that create a micro-vibrational field in the metal structures of the vessel which affects the attachment of fouling organisms. Ultrasonic antifouling is an emerging technology, and currently there is limited evidence for its applicability as a marine growth prevention system on ships. An ultrasonic antifouling system may potentially be effective in reducing fouling of niche areas like propellers, sea chests, seawater pipes, and cooling systems.

The objective of this initial evaluation was to elucidate the potential benefits and limitations of ultrasonic antifouling systems. Ultrasonic transducers were installed in the seawater cooling system, around the propeller shaft, and on the inside of the underwater hull surface of the crude oil tanker HAFNIA GALATEA (IMO: 9796975).

Furthermore, ultrasonic transducers were installed on the inside of the hull of the diving vessel EARL 3 (MMSI: 563044170).

The voyage schedule of HAFNIA GALATEA provided practical constraints for the inspection and assessment of fouling. A test site was therefore established in a harbour in South Fremantle, Western Australia, and ultrasonic transducers were mounted on steel panels that were easily accessible for inspection.

Commercial shipping is a major contributor to underwater radiated noise which is known to cause adverse effects on marine animals including mammals, fish and invertebrates. The impact of underwater noise on marine life is an area of increasing environmental importance (United Nations, 2018; IMO, 2024). Underwater noise generated by ships is typically associated with propellers, hull form, onboard machinery, wake flow, and operational and maintenance activities (IMO, 2024). The underwater noise emitted by ultrasonic antifouling systems may affect marine mammals such as whales (Trickey *et al.,* 2022), especially if the frequency of the system overlaps with the area of best hearing of the species. The impacts on marine mammals may comprise behavioural responses to the emitted noise or more severe hearing impairment. This study evaluated the potential environmental side effects related to the underwater sound emitted from the ultrasonic antifouling systems installed onboard HAFNIA GALATEA and EARL 3.

The project was led by DHI, an independent, international research and consulting organization. DHI measured the sound emitted from the ultrasonic antifouling system and evaluated the adverse effects of underwater noise on marine mammals. ALLSET Industries, a Danish maritime service provider with offices in Australia and Singapore, provided and installed the ultrasonic antifouling system, and evaluated fouling of submerged panels in South Fremantle, Western Australia. Hafnia, a global shipping operator of product and chemical tankers, founded in Denmark, made the crude oil tanker HAFNIA GALATEA available for installation of the ultrasonic antifouling system and evaluated the fouling of the areas onboard HAFNIA GALATEA receiving ultrasonic treatment.

The study was funded by a grant from the Danish Maritime Fund.

2 Materials and methods

2.1 Ultrasonic antifouling system

Ultrasonic antifouling transducers and control units were installed onboard the test vessels by ALLSET Industries. The ultrasonic transducers were manufactured by Ultraguard (United Kingdom). The Ultraguard series UG 120/20 (120 watts, 20 kHz) and UG 100/28 (100 watts, 28 kHz) used in the study deliver 16 pulses per second. The UG 120/20 transducer has a diameter of 89 mm and a height of 100 mm. The UG 100/28 transducer has a diameter of 79 mm and a height of 80 mm.

2.2 Test vessels

2.2.1 HAFNIA GALATEA

The ultrasonic antifouling system was installed on the crude oil tanker HAFNIA GALATEA (IMO: 9796975) sailing under the flag of Singapore. The length of HAFNIA GALATEA is 249.9 meters, and the width is 44.05 meters.

The ultrasonic antifouling system was installed onboard HAFNIA GALATEA during stay at the Asyad Drydocks, Port of Duqm in Oman (Figure 2.1). The installation was completed on 7th April 2024, and ultrasonic transducers were placed as described below.

Figure 2.1 HAFNIA GALATEA in Port of Duqm, Oman.

High sea chest (starboard side) and low sea chest (port side). A sea chest is a cavity built into the vessel's hull which serves as a reservoir to help the efficiency of pumping seawater into the internal piping. The **sea chest strainer** is a filter in the pipe leading from the sea chest to the cooling system. The intake seawater is used for engine cooling, ballast, and firefighting systems.

Eight transducers (UG 120/20) were installed in connection with the high sea chest at (1) top of high sea chest, (2) mid of side of high sea chest towards aft, (3) top of high sea chest side towards port side, (4) bottom of high sea chest towards port side, (5) top of strainer pipe before filter, (6) top of strainer pipe after filter, (7) side of the top of filter, and (8) side of the bottom of filter.

Six transducers (UG 120/20) were installed in connection with the low sea chest at (1) top of low sea chest, (2) top of low sea chest, (3) strainer pipe before filter, (4) strainer pipe after filter, (5) side of the top of filter, and (6) side of the bottom of filter.

Seawater cooling system, strainer pipe. Two transducers (UG 120/20) were installed in the middle of the pipe, one towards the port side and one towards the starboard side.

Central freshwater coolers / Low temperature (LT) coolers, No. 1 and No. 2. A freshwater circuit cools the heat-generating equipment such as the main engine. In this process, the temperature of the freshwater cooling water increases, and the fresh water is cooled by using seawater as coolant and heat exchange in the central freshwater cooler. Four transducers (UG 100/28) were installed in connection with the LT cooler at (1) top of inlet pipe LT cooler 1, (2) top of outlet pipe LT cooler 1, (3) top of inlet pipe LT cooler 2, and (4) top of outlet pipe LT cooler 2 (Figure 2.2).

Vacuum condenser, seawater cooling system. Four transducers (UG 120/20) were installed in connection with the vacuum condenser: Two at the top of pipe by the vacuum condenser and two at the top of pipe by the main vacuum.

Cargo oil pump turbine (COPT) vacuum condenser. The COPT vacuum condenser generates back-pressure for improving turbine performance and condensed steam. Two transducers (one UG 100/28 and one UG 120/20) were installed on the side of the pipe at the COPT vacuum condenser.

Air ejector condenser. The air ejector condenser draws out the air which is released from condensing the steam. If not removed, the air would cause corrosion. Two transducers (one UG 100/28 and one UG 120/20) were installed on the side of the pipe at the air ejector condenser.

Propeller shaft. Six transducers (UG 120/20) were installed on the stern tube sealing ring, located at the aft-most part of the vessel, around the propeller shaft (Figure 2.3).

Hull. Two transducers (UG 120/20) were installed on the inside of the hull near the propeller shaft, one on the starboard side and one on the port side.

Figure 2.2 Ultrasonic transducer installed on top of pipe leading to low-temperature (LT) cooler No. 1.

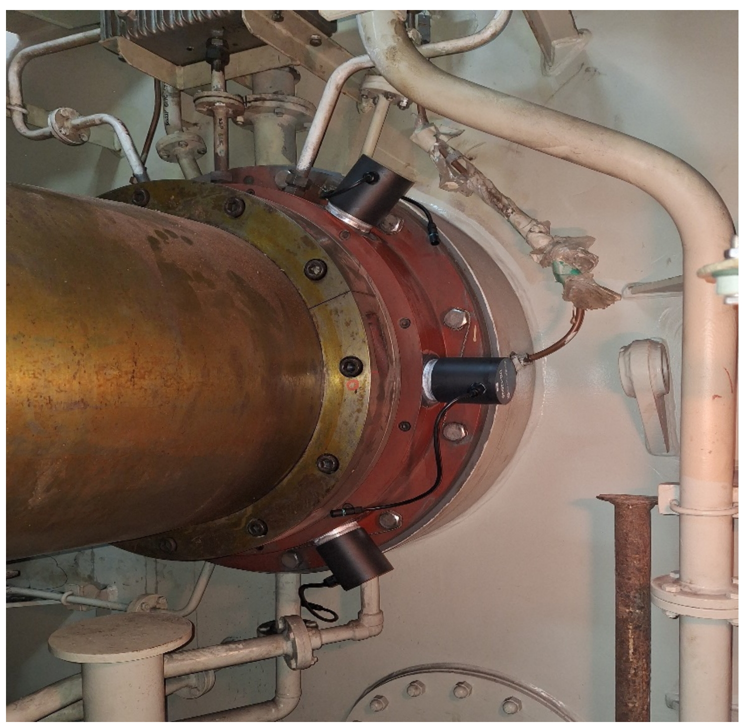

Figure 2.3 Ultrasonic transducer mounted around the propeller shaft.

The marine growth prevention system onboard HAFNIA GALATEA is based on electrolysis and consists of copper and aluminium anodes. The copper anodes produce copper ions that dissolve in the seawater and prevent marine fouling in the seawater cooling system. The aluminium anodes produce aluminium ions that form a noncorrosive layer of aluminium hydroxide and prevent corrosion. To verify the efficacy of the ultrasonic transducers to prevent marine growth, the copper anodes in the marine growth prevention system were turned off.

2.2.2 EARL 3

The diving vessel EARL 3 (MMSI: 563044170, Figure 2.4) was made available for the installation of the ultrasonic antifouling system by Fisk Tech, a service provider in the Port of Singapore. EARL 3 is a catamaran with a length of 20 meters and two parallel hulls of equal size. Four ultrasonic transducers (UG 120/20) were mounted on the left and right inner surfaces of the port side hull in March 2024 (Figure 2.5).

Figure 2.4 EARL 3 outside Port of Singapore.

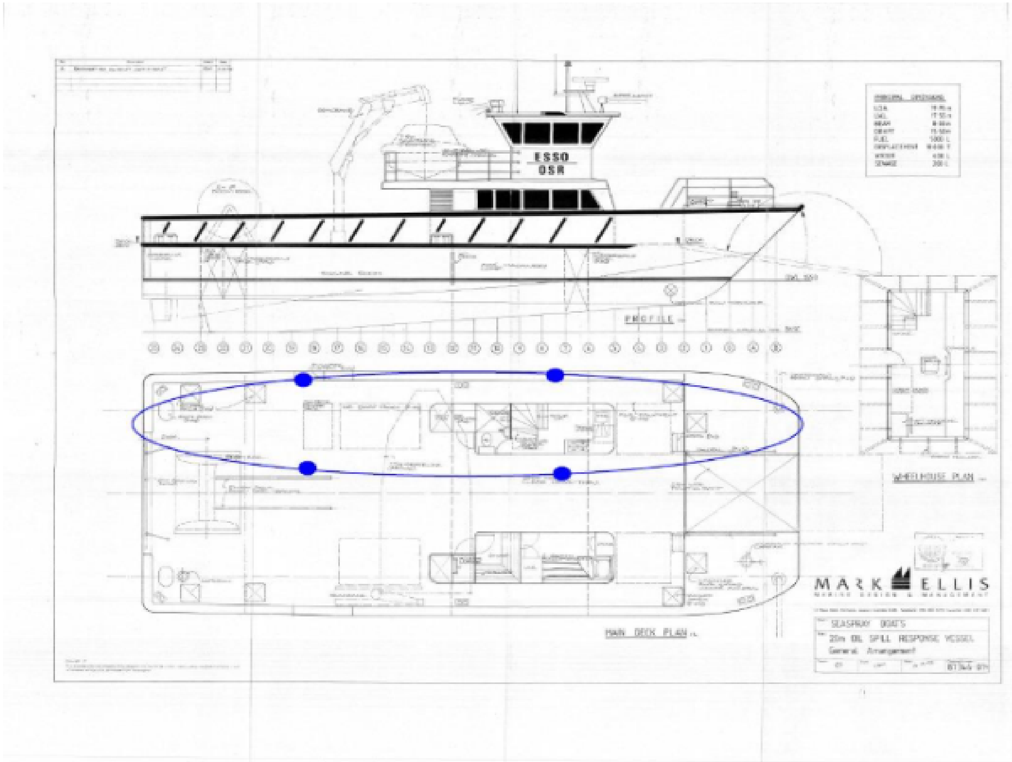

Figure 2.5 **Positioning of four ultrasonic transducers installed on the inner surfaces of the port side hull of the catamaran EARL 3.**

2.3 Harbour test of ultrasonic antifouling system

The efficacy of the ultrasonic antifouling system was examined at a harbour test site providing easy access for inspections. The testing was performed in the Sea Harvest Yard, within the Fremantle Fishing Boat Harbour, in South Fremantle, Perth, Western Australia. This maritime facility is situated in a sheltered marine location with regular vessel activity and naturally nutrient-rich water. The sea temperatures in Fremantle typically range between 18°C and 24°C during April, May and June. The salinity is normally 34-36 practical salinity units (PSU), and the turbidity is moderate due to harbour activity and sediment resuspension.

Steel panels were covered with an aliphatic acrylic polyurethane coating (Jotun Hardtop Ultra) on both sides. Three test panels, each 150 cm x 30 cm, were fixed to a crossbar, and two ultrasonic transducers (UG 120/20) were mounted on two of the panels (Figure 2.6). The test panels were fastened at the quay leaving one transducer above and the other transducer below the water surface (Figure 2.7). Test areas of 30 cm x 30 cm were marked on the submersed part of the test panels with ultrasonic transducers. A separate control panel without ultrasonic transducer and with a size of 30 cm x 30 cm was placed at the quay at the same water depth as the test areas and approx. 10 m from the test panels.

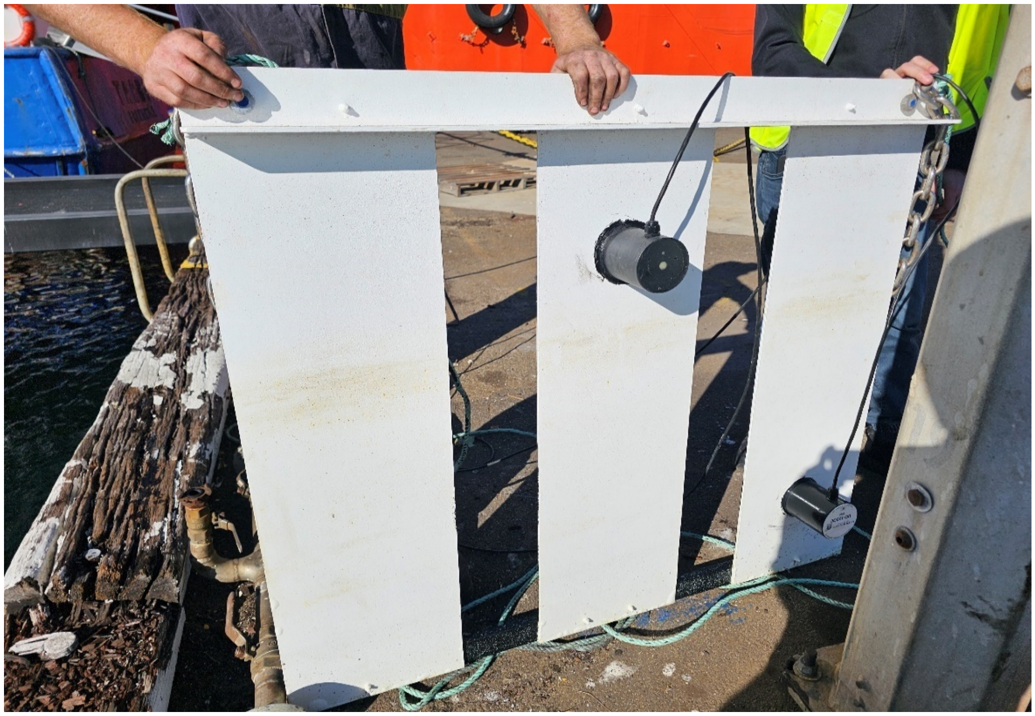

Figure 2.6 Ultrasonic transducers glued on test panels.

Figure 2.7 Test panels with ultrasonic transducers, one above and one below the water surface, in the Sea Harvest Yard, South Fremantle.

The part of the harbour used for the testing is characterized by semi-diurnal tides with a water level variation of about 30 cm. Dependent on the tides, the investigated areas of 30 cm x 30 cm on the panels were covered with 10 to 40 cm water during the entire test. The test and control panels were oriented towards East. All the panels received direct sun exposure for 6 to 10 hours during the day, dependent on weather conditions, except when vessels were occasionally moored and blocked some of the sunlight.

The panels were submersed on 4th April 2025, and the testing ended after 69 days on 12th June 2025.

2.4 Assessment of marine growth prevention efficacy

The marine growth prevention efficacy of the ultrasonic transducers installed onboard HAFNIA GALATEA was monitored by the crew in connection with the normal inspection and cleaning routines of the vessel. The fouling condition of the niche areas treated with the ultrasonic antifouling system was documented by pictures. The crew was instructed to use the fouling rating scale published in the *2023 Guidelines for the control and management of ship's biofouling to minimize the transfer of invasive aquatic species* (Table 2.1) and to provide comments on their observations.

The marine growth on the submerged panels in the Sea Harvest Yard in South Fremantle, Perth, Western Australia, was monitored by ALLSET Industries and documented with pictures.

Table 2.1 Fouling rating to assess the extent of fouling by visual inspection.

Rating	Description	Macrofouling cover of area
0	**No fouling** Surface entirely clean. No visible biofouling on surfaces.	-
1	**Microfouling** Submerged areas partially or entirely covered in microfouling. Metal and painted surface may be visible beneath the fouling.	-
2	**Light macrofouling** Presence of microfouling and multiple macrofouling patches. Fouling species cannot be easily wiped off by hand.	1-15% of surface
3	**Medium macrofouling** Presence of microfouling and multiple macrofouling patches.	16-40% of surface
4	**Heavy macrofouling** Large patches or submerged areas entirely covered in macrofouling.	41-100% of surface

Reference: IMO, 2023.

2.5 Assessment of environmental impact of underwater noise

2.5.1 Measurements of underwater sound

The sound emitted from the ultrasonic transducers was measured by use of a DHI survey vessel and a Sound Trap ST600 HF (Ocean Instruments[NZ]) underwater sound recorder. The engine of the DHI survey vessel was set in neutral gear during the sound measurements, as turning the engine off would conflict with safety precautions.

The sound from the ultrasonic transducers onboard HAFNIA GALATEA was measured, when the tanker was anchored at the Eastern Petroleum A Anchorage in the Singapore Strait at the coordinates N 01.25631° and E 103.9212°. During the measurements the engine of HAFNIA GALATEA was turned off. The water depth at this location was approx. 50 m. The sound measurements were performed on 15th February 2025 in a depth of 5 m below the sea surface and at distances of 50 m, 150 m, 300 m, 600 m, and 1000 m in perpendicular direction from HAFNIA GALATEA's keel line. The transducer settings during the sound measurements were: (i) transducers in cooling system and at propeller off, (ii) transducers in cooling system on and at propeller off, and (iii) transducers in cooling system and at propeller on.

Additional measurements were taken in the aft direction in the keel line at distances of 20 m, 50 m, and 150 m. These measurements were taken with the transducer settings: (i) transducers in cooling system and at propeller off and (ii) transducers in cooling system off and at propeller on.

The duration of each sound measurement at HAFNIA GALATEA was 4-5 min. The sound recordings were sampled at a sampling rate of $f_s = 384\ kHz$.

The sound from the ultrasonic transducers onboard EARL 3 was measured in the Singapore Strait at the coordinates N 01.22131° and E 103.74324°. During the measurements the engine of EARL 3 was turned off, while a generator located on the port side and used for powering the ultrasonic transducers remained on. The water depth at this location was approx. 20 meters. The sound measurements were performed on 11th December 2024 in two depths, 2 m and 5 m below the sea surface, at distances of 20 m, 50 m, 250 m, 1000 m, and 1800 m from EARL 3. At the closest position (20 m) and the most distant position (1800 m) from EARL 3, the sound was measured with the transducers turned off and on. The duration of each sound measurement was 4-5 min. The sound recordings were characterized by a sampling rate describing the number of discrete samples taken within a defined time.

The recordings of the sound from the transducers onboard EARL 3 were sampled at a sampling rate of $f_s = 192\ kHz$.

The sound data were analysed in spectrograms showing the emitted frequencies, and the sound exposure level was expressed as the sound pressure level, SPL (Appendix A).

2.5.2 Description of the sound source

To enable the modelling of noise emissions and the assessment of impacts on marine mammals, a description of the sound source is a prerequisite. For both measured and modelled data, a single omnidirectional point source was assumed. A directionality of the noise emissions can be expected, as wave lengths are short compared to the geometrical features of the vessels. In case of HAFNIA GALATEA there is considerable distance between the transducers in the seawater cooling system and those at the propeller. However, all transducers onboard HAFNIA GALATEA were considered as a single point source, because quantification of the source levels from the transducers at the propeller was difficult due to the uncertainty related to the measurement distance. Merging all transducers into a single point source is reasonable, as the sound recordings indicate that the emissions were dominated by the transducers in the seawater cooling system.

The source is assumed to be located at 5-m depth for HAFNIA GALATEA and 1-m depth for EARL 3.

For the modelling, the 1/3 octave bands centred at 20 kHz, 25 kHz, 31.5 kHz and 40 kHz were considered, and the source levels were derived by backpropagating the mean levels recorded at the closest distances where spherical spreading can be assumed, and volume attenuation can be neglected. This means that the source level SL_f for a centre frequency f can be derived as

$$SL_f = RL_{cr,f} + 20\log_{10} r_{cr}$$

where $RL_{cr,f}$ denotes the received level at close range for the considered centre frequency, and r_{cr} denotes the distance from the source point to the measurement location.

The above considerations yield the source spectra shown in Figure 2.8. The broadband source levels in the considered frequency range are 170.5 dB re 1 µPa for HAFNIA GALATEA and 158.6 dB re 1 µPa for EARL 3. The difference in the source levels is consistent with the difference in injected electrical power and the number of transducers that are considerably higher for HAFNIA GALATEA.

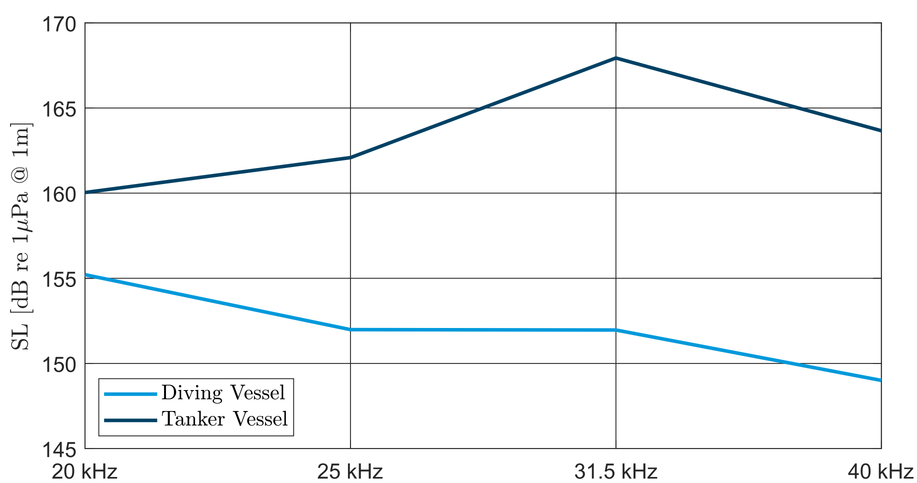

Figure 2.8 Source spectra for sound emitted from ultrasonic transducers onboard HAFNIA GALATEA (Tanker Vessel) and EARL 3 (Diving Vessel).

2.5.3 Modelling of underwater noise propagation

The water column can be viewed as a sound duct bounded by the water surface and the partially absorptive seabed. The efficacy of underwater sound propagation depends on several environmental factors such as water depth, salinity, acidity, temperature, and the composition of the sediment. The sound fields from the same source depend on the time and location of the emission which means that different propagation characteristics are expected in tropical shallow waters and arctic deep waters, or they may vary by season. To enable predictions for different scenarios, a two-step modelling approach was employed in which the source levels derived in Section 2.5.2 were combined with numerical propagation models. Sound propagation models were developed for the Singapore Strait and the Skagerrak which is a strait between the Jutland peninsula of Denmark, the east coast of Norway and the west coast of Sweden.

Numerical modelling

The sound propagation models were facilitated by DHI's numerical underwater sound modelling software, MIKE UAS. The software applies a range-dependent acoustic model which is based on the parabolic equation method assuming that the emitted energy dominates over the backscattered energy.

The main features of MIKE UAS are summarized below:

- MIKE UAS accounts for the change in the speed of sound and volume attenuation in the water
- MIKE UAS includes sound propagation in the seabed
- The model calculates the sound propagation in discrete angular directions at individual 2-dimensional (2D) transects
- Specific 1/3 octave bands with centre frequencies from 20 kHz to 40 kHz are modelled.

Range averaging

The modelling was performed for the centre frequencies of each 1/3 octave band only, although many frequencies within each band are excited by the transducers. This approach potentially reduces the accuracy of the results. Carrying out the calculations for multiple frequencies within a band at the expense of increased computational burden could increase the accuracy. However, range averaging has previously been confirmed equivalent to frequency averaging (Harrison and Harrison, 1995). To obtain the most accurate estimates while minimizing the computational effort, a range averaging scheme was applied to the modelling results. Based on a recent study, the averaging was performed over a boxcar window of 10% width of the horizontal distance from the source (Zykov and Bruce, 2024).

Further details related to the modelling of underwater noise propagation are described in Appendix B.

2.5.4 Assessment of noise impact on marine mammals

The impact assessment was performed for marine mammals represented by a group of whales known as cetaceans. Cetaceans can be divided into three different hearing groups based on their hearing ability which is characterized by a generalized hearing range for the entire hearing group (Table 2.2).

Table 2.2 Generalized hearing ranges for marine mammal hearing groups.

Hearing group	Generalized hearing range *
Low-frequency cetaceans (example: humpback whale)	7 Hz to 35 kHz
High-frequency cetaceans (example: killer whale)	150 Hz to 160 kHz
Very high-frequency cetaceans (example: harbour porpoise)	275 Hz to 160 kHz

Note: * Generalized hearing range for the entire group including all species within the group. Individual species' hearing ranges are typically not as broad; for details, see Southall *et al.,* 2007.

Reference: NMFS, 2024.

Investigated noise effects

Several overlapping zones of biological impacts can be distinguished and depend largely on the distance from the sound source to the exposed animal (Thomsen *et al.*, 2021). The different impact zones are:

- *Zone of masking*: The area where noise interferes with the detection of biologically relevant signals used by marine animals for communication and navigation.

- *Zone of behavioural response*: The area within which a marine animal changes its behaviour in response to noise, e.g., by swimming away or diving deeper. Repetitive and/or continuous behavioural avoidance can lead to distribution changes of the species affected by the noise disturbance. This effect can be temporary (Brandt *et al.,* 2011) or long-term (Morton and Symonds, 2002).

- *Zone of impaired hearing*: The area in which noise can lead to hearing impairment such as temporary threshold shift or auditory injury.

- *Zone of physical and/or physiological effects*: The area where tissue damage and physiological effects other than those associated with hearing can occur. In extreme cases, the damage can lead to the death of the marine animal.

Thresholds for noise impact

Underwater noise impact thresholds describe received levels of noise which should not be exceeded to prevent harm to marine life. Threshold values were based on frequency weighting considering that animal hearing sensitivity is frequency dependent.

The behavioural response thresholds for the low-frequency- and high-frequency hearing groups were based on available data from studies on cetacean reactions to continuous sounds (Southall *et al.,* 2007 and 2021). For very high-frequency cetaceans a threshold developed for harbour porpoise was adopted (Tougaard, 2021), and a weighting function was used to derive a weighted sound pressure level (Southall *et al.*, 2019).

The temporary threshold shifts and auditory injury thresholds for low-, high-, and very high-frequency cetaceans used in this study were based on criteria proposed by the National Marine Fisheries Service (NMFS, 2024):

- *Temporary threshold shift* is a temporary hearing impairment, i.e., a reversible increase in the threshold of an individual's capability of hearing or perceiving sounds at a certain frequency.

- *Auditory injury* is associated with damage to the inner ear which may or may not result in a permanent threshold shift, or permanent hearing impairment, i.e., an irreversible increase in the threshold of an individual's capability of hearing or perceiving sounds at a certain frequency.

The impact thresholds used in this study are summarized in Table 2.3.

A behavioural response depends on the immediately received sound pressure. Therefore, behavioural changes are best described in terms of *sound pressure levels* (SPL).

Temporary threshold shift and auditory injury depend on the overall received acoustic energy. Acoustic energy is best expressed as *sound exposure levels* (SEL) because it describes the received sound over time.

Table 2.3 Overview of impact thresholds used to calculate the impact ranges. Impact thresholds are expressed as sound pressure levels (SPL) or sound exposure levels (SEL).

Hearing group	Effect	Sound pressure level [dB re 1 μPa] or Sound exposure level [dB re 1μPa^{2}s]
Low-frequency cetaceans	Onset of behavioural response	*SPL: 130 dB re 1 μPa (1) (2)
	Temporary threshold shift	***SEL: 177 dB re 1μPa^{2}s (3)
	Auditory injury	***SEL: 197 dB re 1μPa^{2}s (3)
High-frequency cetaceans	Onset of behavioural response	*SPL: 130 dB re 1 μPa (1) (2)
	Temporary threshold shift	***SEL*: 181 dB re 1μPa^{2}s (3)
	Auditory injury	***SEL: 201 dB re 1μPa^{2}s (3)
Very high-frequency cetaceans	Onset of behavioural response	**SPL: 103 dB re 1 μPa (4) (5)
	Temporary threshold shift	***SEL: 161 dB re 1μPa^{2}s (3)
	Auditory injury	***SEL: 181 dB re 1μPa^{2}s (3)

Notes: * unweighted SPL; **very high-frequency weighted SPL (based on the weighting function in reference 5); ***weighted cumulative SEL.
References: (1) Southall et al. 2007; (2) Southall et al. 2021; (3) NMFS, 2024; (4) Tougaard, 2021; (5) Southall et al. 2019.

The present assessment focusses on determining impact ranges for behavioural response and hearing impairment as these effects are commonly the basis for regulation where it exists. The methods used for the impact assessment are detailed in Appendix C.

3 Marine growth prevention efficacy of ultrasonic transducers

3.1 HAFNIA GALATEA installation

Ultrasonic antifouling transducers were installed in the entire seawater cooling system, around the propeller shaft, and on the inside of the hull near the propeller shaft of HAFNIA GALATEA. The regular inspections of the seawater cooling system by the crew indicate that the ultrasonic transducers prevented marine growth in some areas, while this was not the case for other parts of the cooling system.

The high sea chest strainer was inspected and found without marine growth meeting the criteria for fouling rating 0 (Figure 3.1). Inspection of the central freshwater cooler showed minimum marine fouling on the surfaces of the cooler plates which could be removed by manual cleaning. The assessment by the crew stated fouling rating 2 for the cooler plates which implies the presence of patches of macrofouling, although macrofouling is not visible from the picture (Figure 3.2, left picture). The cooler seawater piping was found without fouling which means fouling rating 0 (Figure 3.2, right picture).

The vacuum condenser was found with light bivalve shells meeting fouling rating 3, whereas no marine growth was observed on the air ejector condenser (Figure 3.3).

The low-temperature (LT) cooler filters Nos. 1 and 2 were found with many bivalve shells captured on the filter mesh, when the filters were opened for cleaning as seen from the pictures of LT cooler filter No. 1 (Figure 3.4). The bivalve shells were caught by the filter mesh and not attached to the vertical structures of the filter. The shells were apparently removed from the water entering the filter which indicates that the fouling protection of the piping leading to the LT cooler filters was insufficient.

The ultrasonic transducers mounted around the propeller shaft were unable to prevent fouling on the propeller blades. The propeller blades were covered with slime and calcareous deposits meeting fouling rating 4 when inspected and cleaned by diver (Figure 3.5).

The efficacy of the transducers installed on the inside of the hull could not be evaluated, as no fouling was seen on the hull irrespective of whether the surface was receiving ultrasonic treatment.

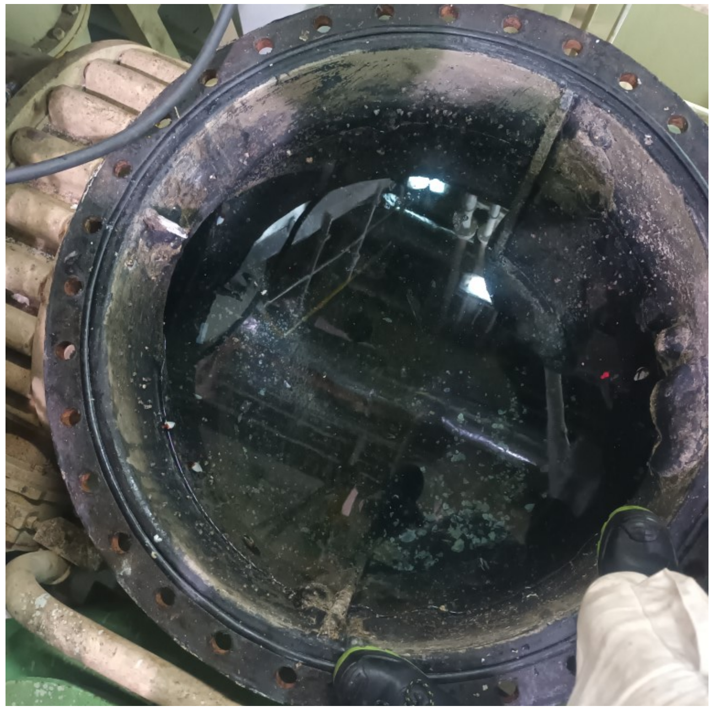

Figure 3.1 **High sea chest strainer found without marine growth, i.e., fouling rating 0, when opened on 16th April 2025.**

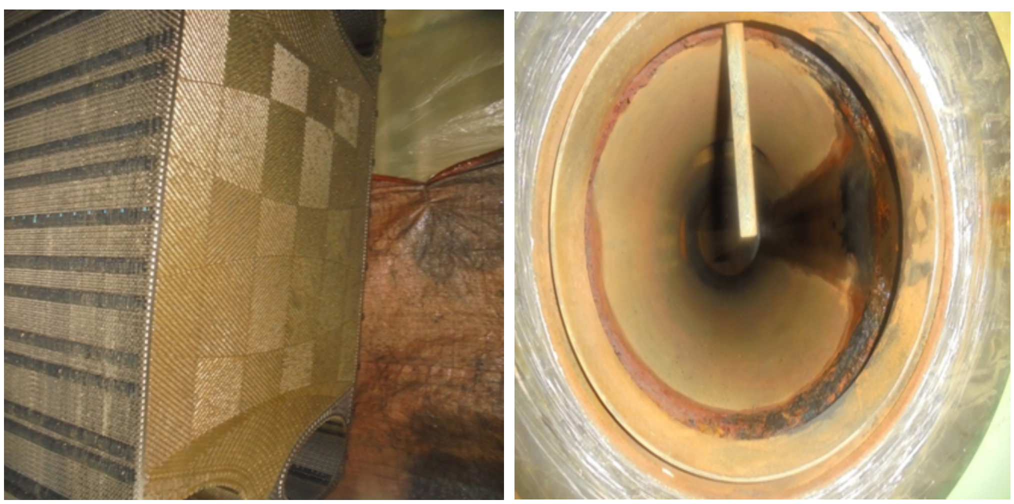

Figure 3.2 **Central freshwater cooler opened for inspection on 2nd September 2024. Cooler plates (left picture) found with marine growth meeting fouling rating 2. Cooler seawater pipe (right picture) found without marine growth, i.e., fouling rating 0.**

Figure 3.3 Vacuum condenser found on 30th August 2024 with light bivalve shells blocking the tubes meeting fouling rating 3 (left picture). Air ejector condenser (right picture) found on 30th August 2024 without marine growth, i.e., fouling rating 0.

Figure 3.4 Low-temperature cooler filter No. 1 found with many bivalve shells captured on the filter mesh, when the filter was opened for cleaning on 17th October 2024 (left picture) and again on 14th April 2025 (right picture).

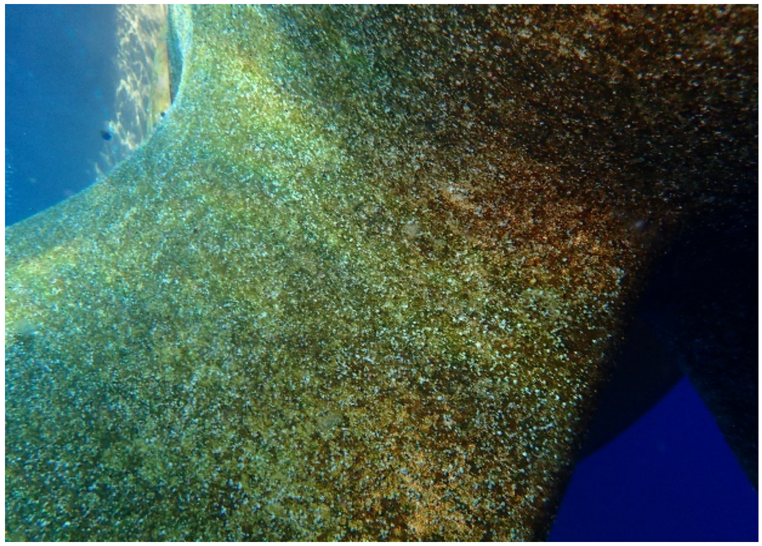

Figure 3.5 Propeller blades covered by slime (approx. 90%), barnacles (approx. 40%), and calcium base deposits (100%) meeting fouling rating 4 when inspected and cleaned by diver on 20th September 2024.

3.2 Harbour installation

The efficacy of the ultrasonic antifouling system was examined in a harbour test conducted in South Fremantle, Perth, Western Australia. The harbour test was initiated on 4th April 2025. Two test panels made of steel and covered with an aliphatic acrylic polyurethane coating were equipped with ultrasonic transducers: One test panel had the transducer mounted above the water surface, while on the other panel, the transducer was mounted below the water surface. Test areas of 30 cm x 30 cm were marked on the submersed part of the test panels. A separate control panel without ultrasonic transducer and with a size of 30 cm x 30 cm was placed at the same water depth.

The ultrasonic transducer prevented fouling on the test panels submersed in marine water in South Fremantle for 69 days (Figure 3.6).

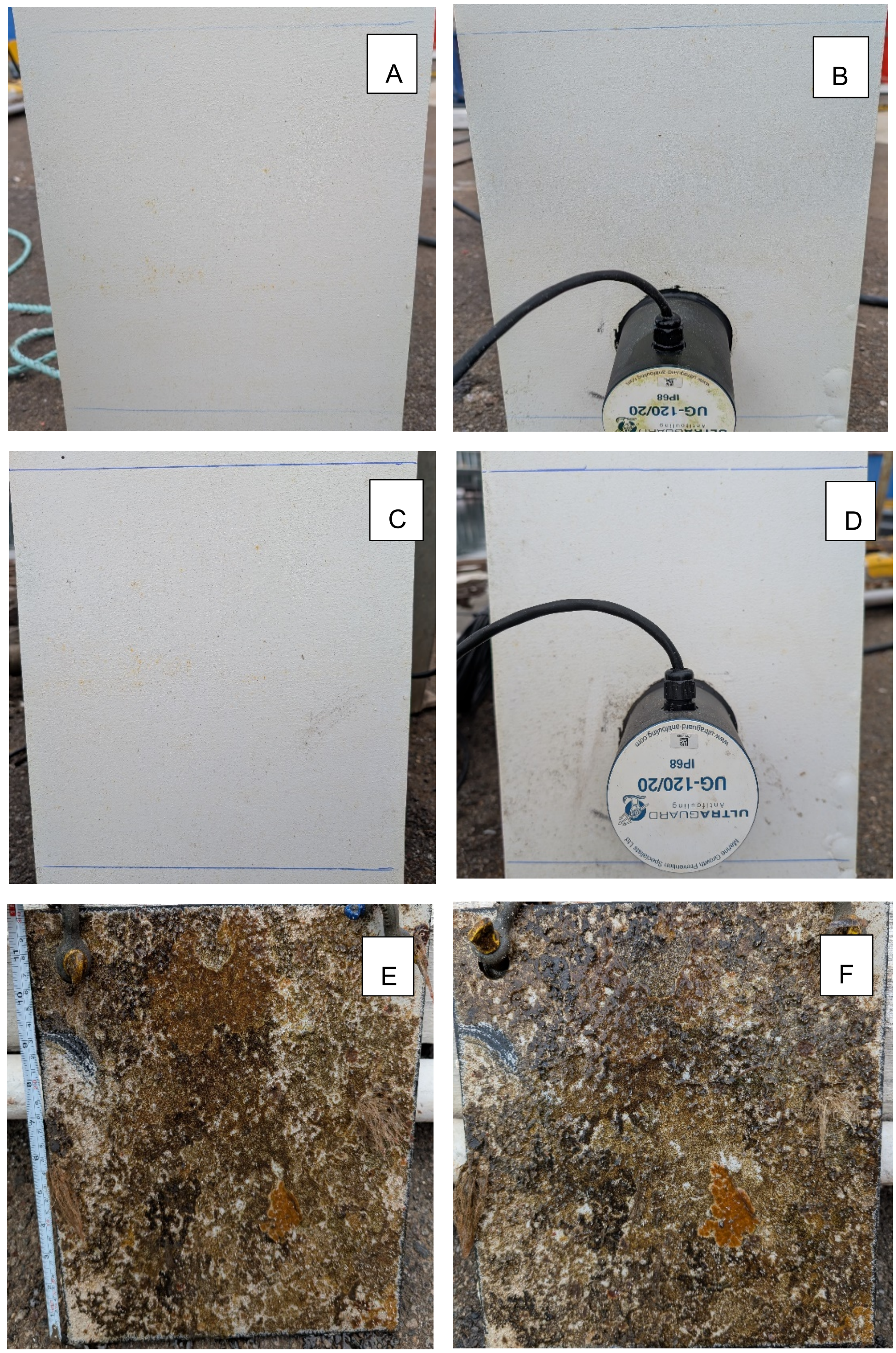

Figure 3.6 **Test and control panels submersed in water in South Fremantle, Western Australia. Test panels were found without fouling after 55 days (A and B) and 69 days (C and D). Control panel was found with heavy macrofouling meeting fouling rating 4 after 55 days (E) and 69 days (F). The ultrasonic transducers were mounted on the test panels above the water surface (A and C) and below the water surface (B and D).**

4 Environmental impact of underwater noise from ultrasonic transducers

4.1 Simulated propagation of underwater radiated noise

The propagation of the noise emitted from the ultrasonic transducers onboard HAFNIA GALATEA and EARL 3 was modelled with centre frequencies from 20 to 40 kHz (Section 2.5.3) and compared with the measured underwater noise on location in the Singapore Strait. The comparisons between modelled and measured sound pressure levels (SPL) in the frequence band centred at 31.5 kHz are shown in Figures 4.1 and 4.2. All the results of the comparison of modelled and measured noise covering the range from 20 to 40 kHz are included in Appendix B. The agreement between the modelled and measured SPL was good considering the uncertainties related to the measurement positions and the composition of the seabed.

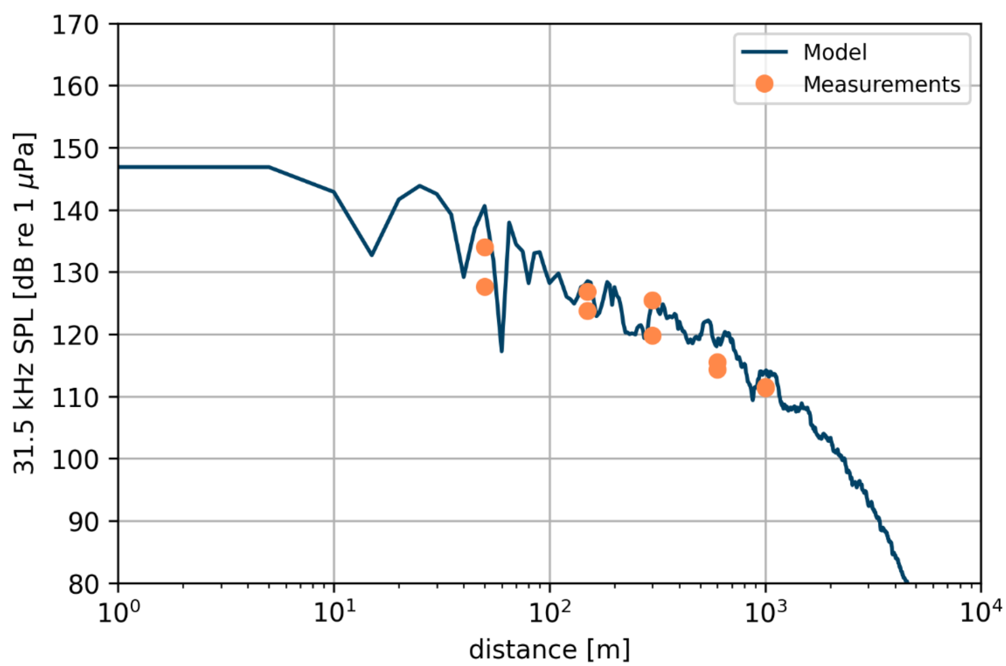

Figure 4.1 Modelled sound pressure levels (SPL) in the Singapore Strait at 5 meters depth in a frequency band centred at 31.5 kHz compared to measured mean SPL for the noise emitted from the ultrasonic transducers onboard HAFNIA GALATEA.

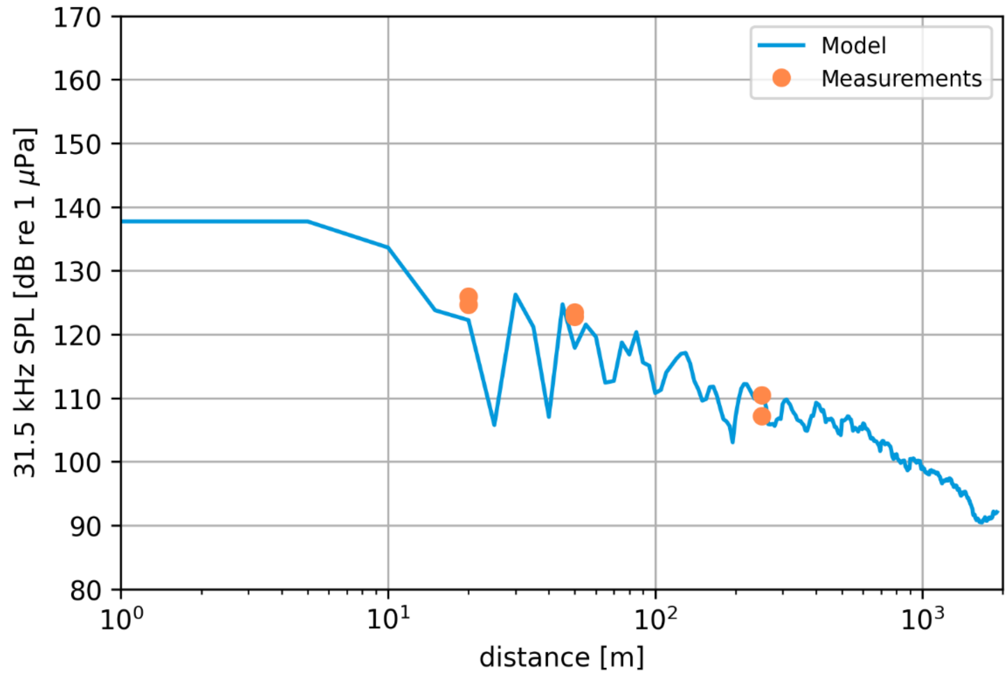

Figure 4.2 Modelled sound pressure levels (SPL) in the Singapore Strait at 5 meters depth in a frequency band centred at 31.5 kHz compared to measured mean SPL for the noise emitted from the ultrasonic transducers onboard EARL 3.

The additional propagation model made for the Skagerrak, described in Appendix B.2, assumes conditions that would likely prevail during a hypothetical voyage of HAFNIA GALATEA through the Skagerrak during winter.

4.2 Effects of underwater noise on marine mammals

4.2.1 Behavioural reactions

The assessment of behavioural reactions of marine mammals was based on comparison of the unweighted or weighted sound pressure levels with the impact thresholds for low-, high- and very high-frequency cetaceans described in Section 2.5.4. Weighted sound pressure levels are derived by taking the hearing of the group of animals, e.g., very high-frequency cetaceans into account (Southall *et al.*, 2019).

The modelled sound pressure levels and the thresholds for behavioural responses to the noise from the ultrasonic transducers onboard HAFNIA GALATEA are shown for low-frequency- and high-frequency cetaceans (Figures 4.3 and 4.4) and harbour porpoise, a very high-frequency cetacean (Figures 4.5 and 4.6).

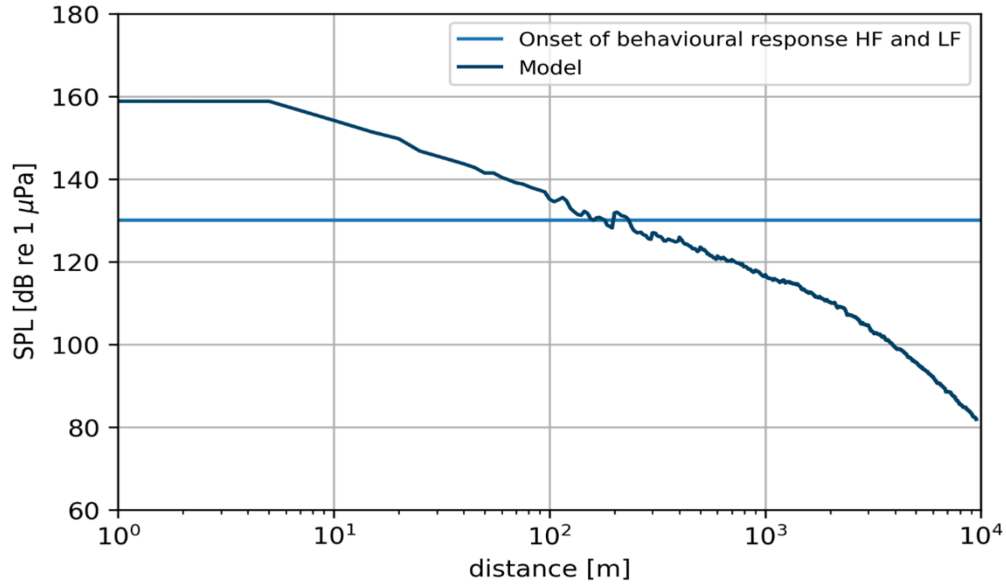

Figure 4.3 **Unweighted modelled sound pressure levels (SPL) in the Singapore Strait for the noise from the ultrasonic transducers onboard HAFNIA GALATEA and threshold for behavioural responses for high-frequency- (HF) and low-frequency (LF) cetaceans.**

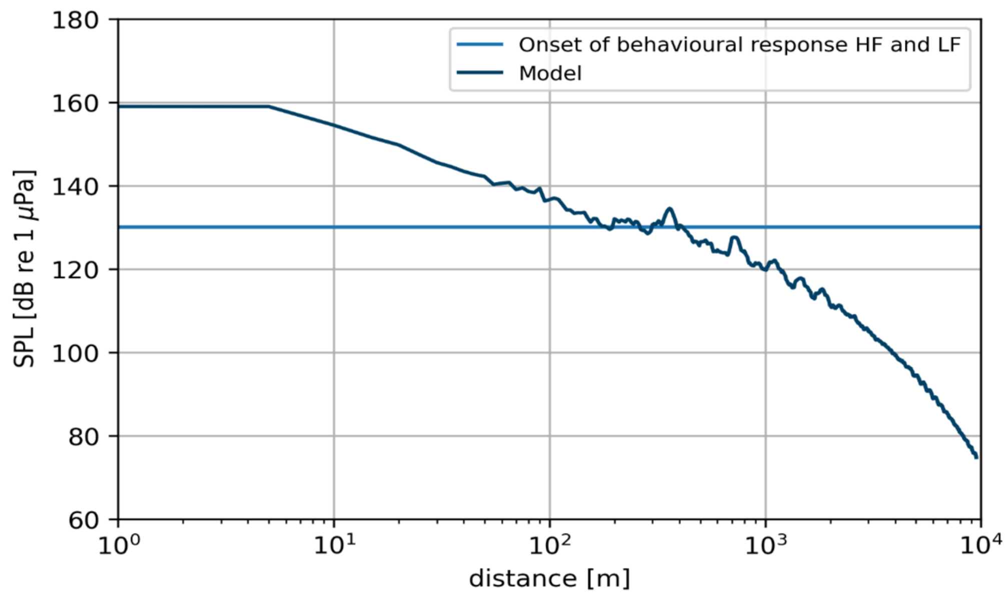

Figure 4.4 **Unweighted modelled sound pressure levels (SPL) in the Skagerrak for the noise from the ultrasonic transducers onboard HAFNIA GALATEA and threshold for behavioural responses for high-frequency- (HF) and low-frequency (LF) cetaceans.**

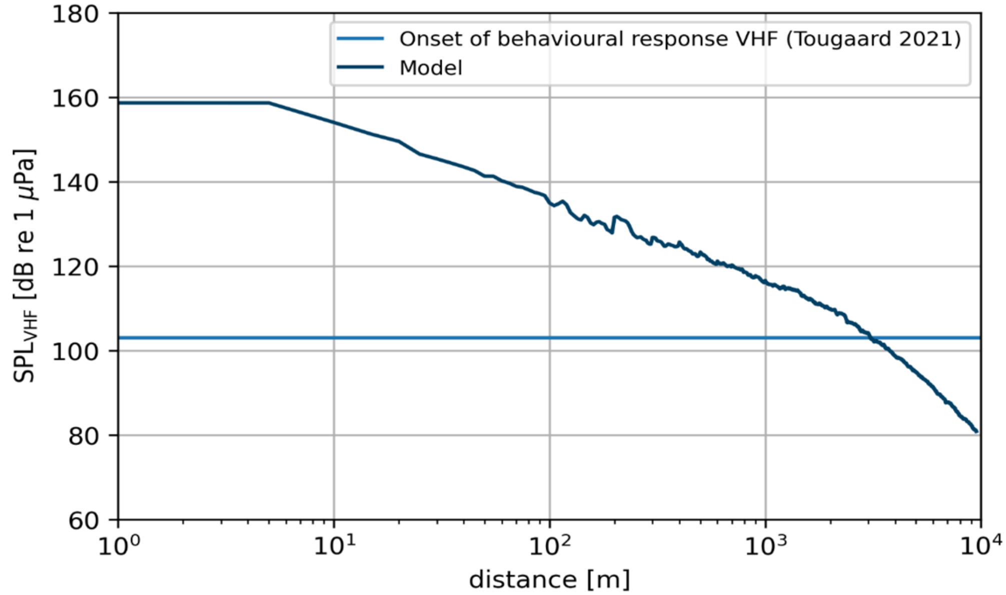

Figure 4.5 **Very high-frequency weighted modelled sound pressure levels (SPL_{VHF}) in the Singapore Strait for the noise from the ultrasonic transducers onboard HAFNIA GALATEA and threshold for behavioural responses for harbour porpoise.**

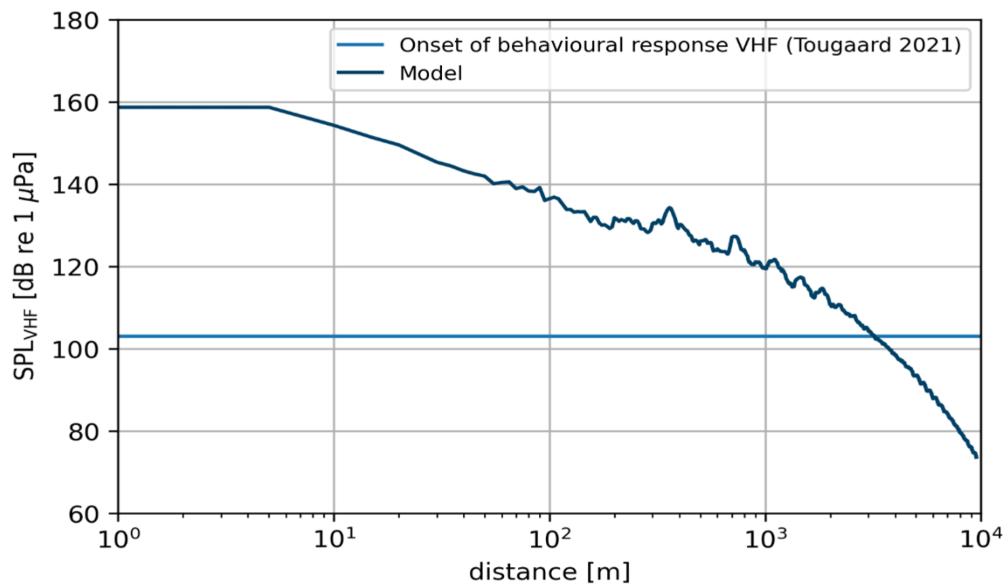

Figure 4.6 **Very high-frequency weighted modelled sound pressure levels (SPL_{VHF}) in the Skagerrak for the noise from the ultrasonic transducers onboard HAFNIA GALATEA and threshold for behavioural responses for harbour porpoise.**

The modelled sound pressure levels and the thresholds for behavioural response for the noise from the ultrasonic transducers onboard EARL 3 are shown for low-frequency- and high-frequency cetaceans (Figure 4.7) and harbour porpoise (Figure 4.8).

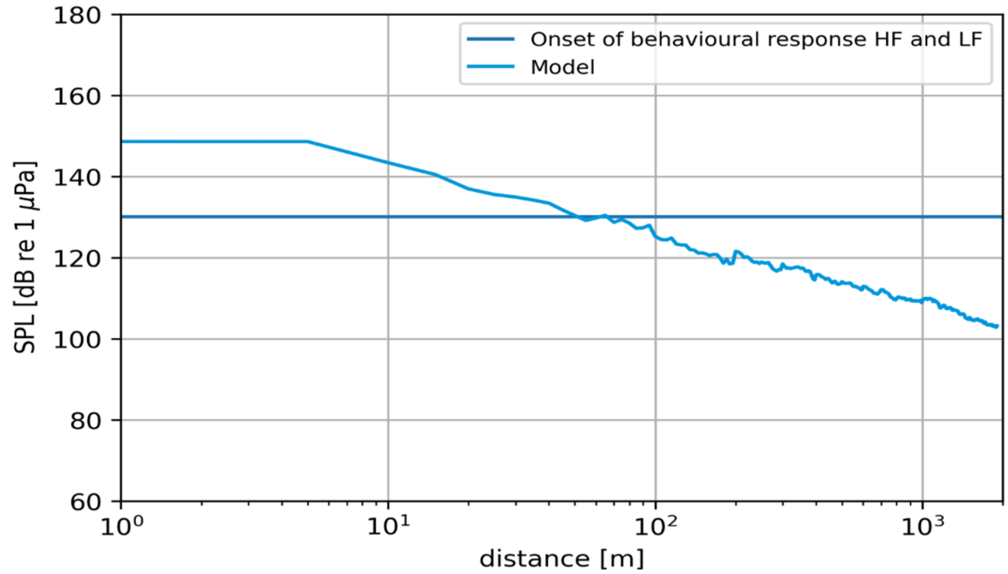

Figure 4.7 Unweighted modelled sound pressure levels (SPL) in the Singapore Strait for the noise from the ultrasonic transducers onboard EARL 3 and threshold for behavioural responses for high-frequency- (HF) and low-frequency (LF) cetaceans.

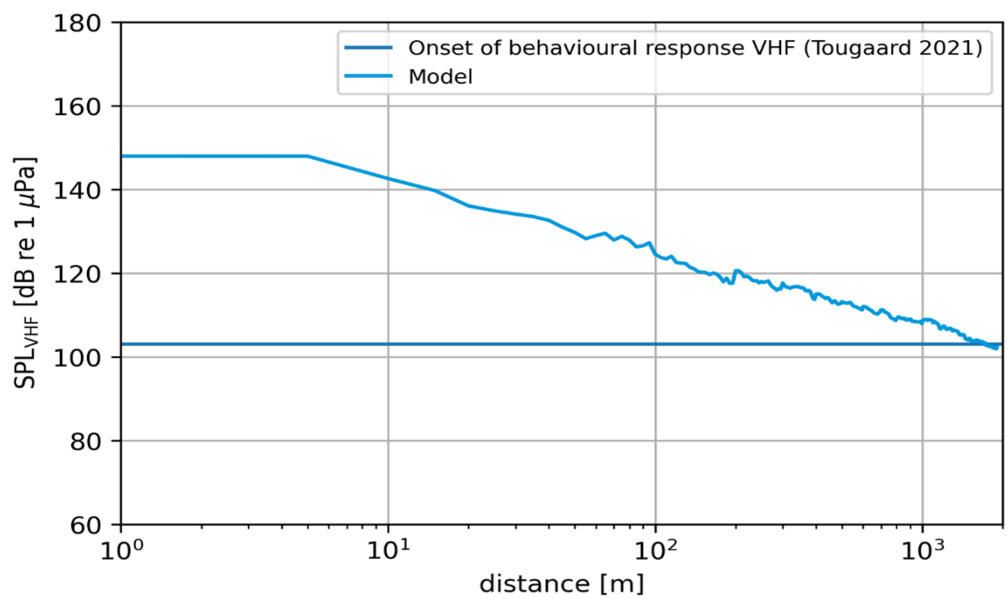

Figure 4.8 Very high-frequency weighted modelled sound pressure levels (SPL_{VHF}) in the Singapore Strait for the noise from the ultrasonic transducers onboard EARL 3 and threshold for behavioural responses for harbour porpoise.

The predicted impacts on marine mammal behaviour are higher for the ultrasonic transducers onboard HAFNIA GALATEA compared to those in EARL 3 (Table 4.1), which may be explained by the higher source level for the noise from the larger number of ultrasonic transducers in HAFNIA GALATEA:

- Behavioural responses for *low-frequency- and high-frequency cetaceans* to noise from the ultrasonic transducers onboard HAFNIA GALATEA may occur within ranges of 230 meters in the Singapore Strait (Figure 4.3) and 410 meters in the Skagerrak (Figure 4.4)

- Behavioural responses for *harbour porpoise* to noise from the ultrasonic transducers onboard HAFNIA GALATEA may occur within ranges of 3075 meters in the Singapore Strait (Figure 4.5) and 3210 meters in the Skagerrak (Figure 4.6)

- Behavioural responses for *low-frequency- and high-frequency cetaceans* to noise from the ultrasonic transducers onboard EARL 3 may occur within a range of 65 meters in the Singapore Strait (Figure 4.7)

- Behavioural response for *harbour porpoise* to noise from the ultrasonic transducers onboard EARL 3 may occur within a range of 1725 meters in the Singapore Strait (Figure 4.8).

4.2.2 Hearing impairment

The assessments of hearing impairment such as *temporary threshold shift* and *auditory injury* were based on cumulative sound exposure levels which increase in proportion to the duration of the exposure. An ultrasonic antifouling system is assumed to be permanently turned on, and the sound will thus be emitted for an indefinite time. Regulations recommend a 24-hour interval for sound exposure as a worst-case scenario. However, while a vessel emitting underwater noise may be static for a long time (e.g., when anchored), this is hardly the case for marine animals that can avoid extended harmful exposure to noise. Using a 24-hour exposure time is therefore considered overly conservative, and instead the following scenarios were used in the impact assessment:

- *Static vessel exposure scenario*. Underwater noise emitted from a static vessel reaching a static marine animal with a cumulated exposure time of 15 minutes.
- *Moving vessel exposure scenario*. Underwater noise emitted from a moving vessel reaching a static marine animal where the cumulation of the received sound depends on the distance between the vessel and the animal.

The cumulative sound exposure levels were adjusted for impulsiveness as described in Appendix C.3.

Static vessel exposure scenario

In the static vessel exposure scenario both the vessel and the marine animal are static, and, e.g., it may be assumed that a vessel at anchorage emits underwater noise leading to 15 minutes exposure of a static marine animal. This exposure scenario leads to hearing impairment of *low-frequency- and high-frequency cetaceans* in the close vicinity of the sound source, as the thresholds for temporary threshold shift were exceeded 5 to 20 meters from the vessel (Table 4.1).

Table 4.1 Predicted ranges of hearing impacts of noise emitted from the ultrasonic transducers onboard HAFNIA GALATEA and EARL 3 assuming that the vessel is static.

Hearing Group	Effect	Impact range [m]		
		HAFNIA GALATEA Singapore Strait	HAFNIA GALATEA Skagerrak	EARL 3 Singapore Strait
Low-frequency cetaceans	Behavioural response	230	410	65
	Temporary threshold shift	5	5	-
	Auditory injury	-	-	-
High-frequency cetaceans	Behavioural response	230	410	65
	Temporary threshold shift	20	20	5
	Auditory injury	-	-	-
Very high-frequency cetaceans	Behavioural response	3075	3210	1725
	Temporary threshold shift	905	1040	300
	Auditory injury	80	90	20

More pronounced effects are predicted for 15 minutes exposure of *very high-frequency cetaceans*, such as harbour porpoise (Table 4.1; Figures 4.9 to 4.11):

- Temporary threshold shifts and auditory injury caused by noise from the ultrasonic transducers onboard HAFNIA GALATEA may occur within ranges of 905 and 80 meters, respectively, in the Singapore Strait (Figure 4.9)

- Temporary threshold shifts and auditory injury caused by noise from the ultrasonic transducers onboard HAFNIA GALATEA may occur within ranges of 1040 and 90 meters, respectively, in the Skagerrak (Figure 4.10)

- Temporary threshold shifts and auditory injury caused by noise from the ultrasonic transducers onboard EARL 3 may occur within ranges of 300 and 20 meters, respectively, in the Singapore Strait (Figure 4.11).

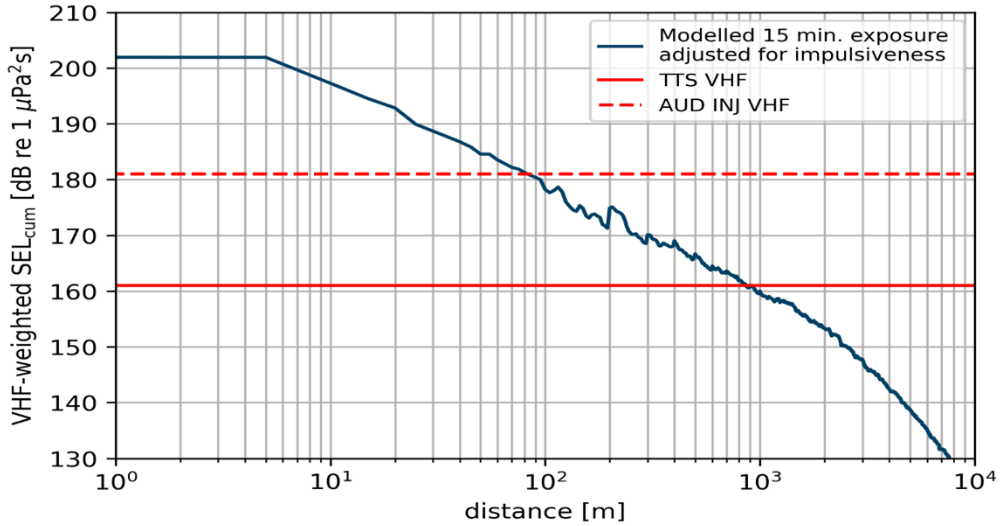

Figure 4.9 **Very high-frequency weighted modelled sound exposure levels (SEL_{cum}) in the Singapore Strait for the noise from the ultrasonic transducers onboard HAFNIA GALATEA and thresholds for temporary threshold shift (TTS VHF) and auditory injury (AUD INJ VHF) for very high-frequency cetaceans.**

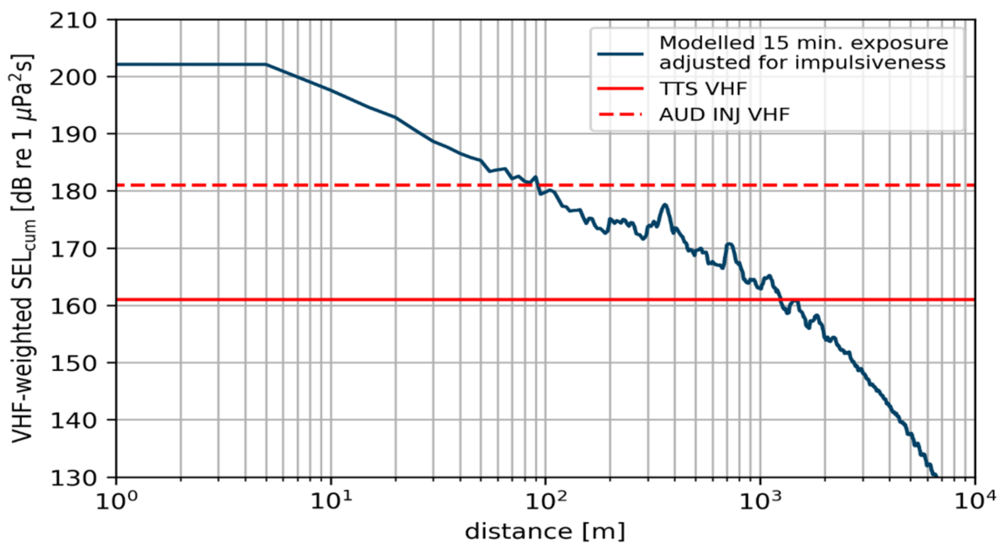

Figure 4.10 **Very high-frequency weighted modelled sound exposure levels (SEL_{cum}) in the Skagerrak for the noise from the ultrasonic transducers onboard HAFNIA GALATEA and thresholds for temporary threshold shift (TTS VHF) and auditory injury (AUD INJ VHF) for very high-frequency cetaceans.**

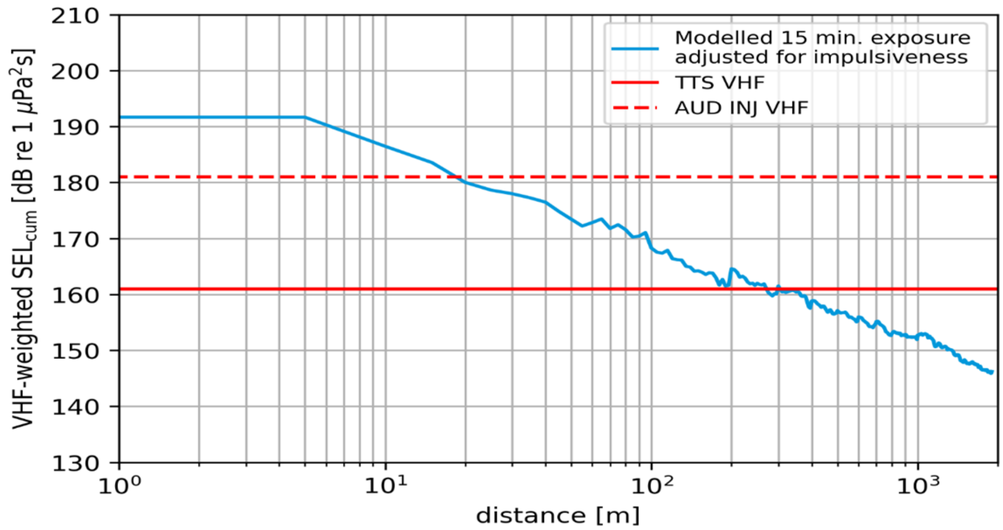

Figure 4.11 Very high-frequency weighted modelled sound exposure levels (SEL$_{cum}$) in the Singapore Strait for the noise from the ultrasonic transducers onboard EARL 3 and thresholds for temporary threshold shift (TTS VHF) and auditory injury (AUD INJ VHF) for very high-frequency cetaceans.

The thresholds for temporary threshold shift and auditory injury were modelled as function of exposure duration and distance to the sound source (Appendix C.5). Taking the data for the ultrasonic transducers onboard HAFNIA GALATEA as example, it is seen that:

- An exposure duration of 100 seconds may cause *temporary threshold shift for very high-frequency cetaceans* at distances up to approx. 300 m in the Singapore Strait and up to approx. 500 m in the Skagerrak

- An exposure duration of 100 seconds may cause *auditory injury for very high-frequency cetaceans* at distances up to approx. 15 m in the Singapore Strait and the Skagerrak.

Temporary threshold shift and auditory injury for low-frequency and high-frequency cetaceans require either close distance to the sound source or long exposure duration (see details in Appendix C.5).

Moving vessel exposure scenario

In the moving vessel exposure scenario, the vessel is assumed to be moving in a straight line at constant speed passing a stationary marine mammal. The closest point of approach (CPA) is the point at which the shortest distance between the moving vessel and the animal is seen (Figure 4.12).

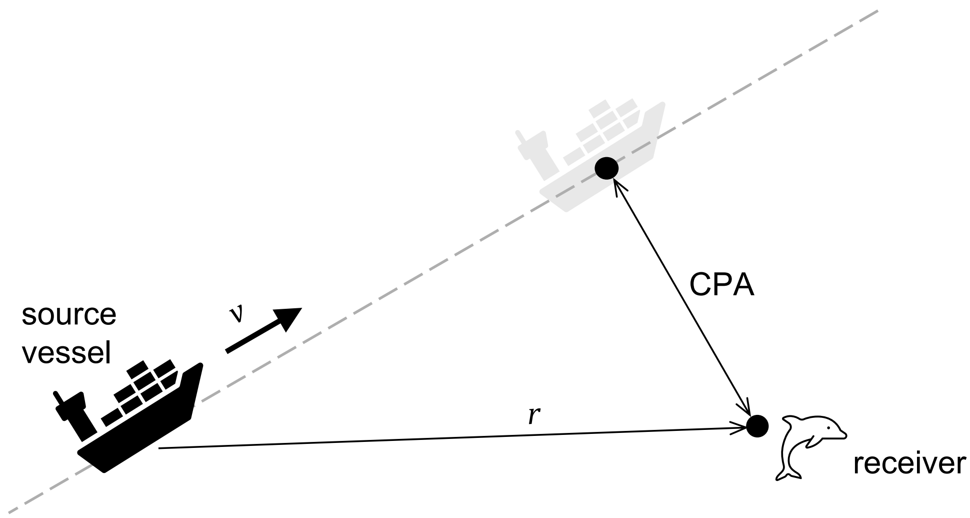

Figure 4.12 Assumed vessel track and closest point of approach (CPA).

The sound exposure level (SEL) resulting from the noise emitted from the ultrasonic transducers increases with decreasing distance r, and thus the maximum SEL is reached at CPA. The cumulative SEL is obtained by integrating this distance dependent SEL over time. The cumulative SEL depends on the vessel speed. Reduced vessel speed increases the cumulative SEL, as the time for the vessel's passing of the marine animal increases (assuming the emissions from the ultrasonic transducers are independent of vessel speed).

Figure 4.13 shows the dependence of the cumulative SEL on the distance between the vessel and a marine animal in a case where HAFNIA GALATEA, with ultrasonic transducers turned on, passes a marine animal in the Skagerrak with a minimum distance of 100 meters and a speed of 15 knots.

The cumulative SEL resulting from the ultrasonic transducers onboard HAFNIA GALATEA is shown as function of the CPA for travels in the Singapore Strait (Figure 4.14) and the Skagerrak (Figure 4.15). It is seen from Figures 4.14 and 4.15 that the threshold for temporary threshold shift (TSS) for very high-frequency cetaceans is exceeded for CPA-distances up to approx. 500 meters (Singapore Strait) and approx. 1000 meters (Skagerrak) dependent on vessel speed.

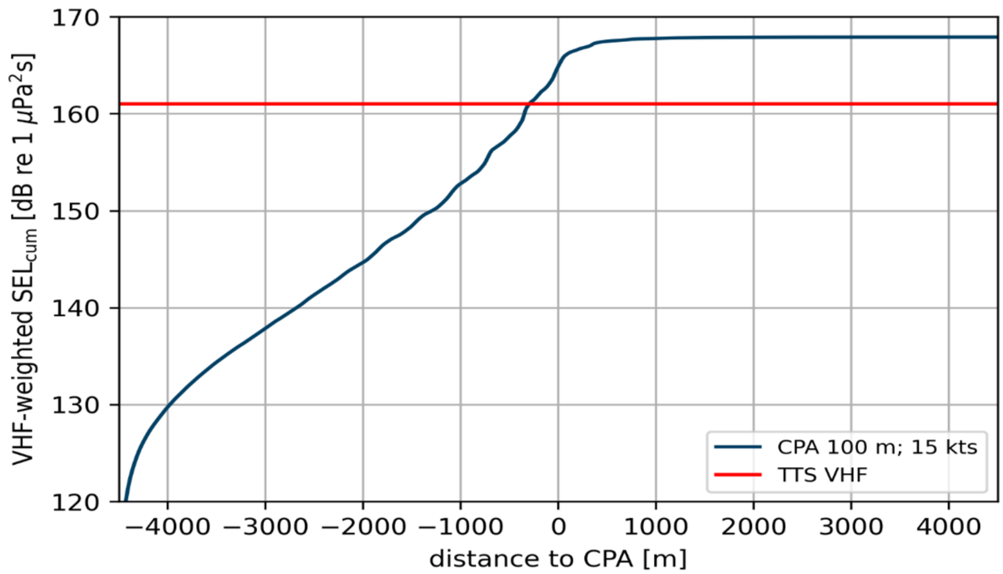

Figure 4.13 **Development of the cumulative sound exposure level (SEL_{cum}, weighted for very high-frequency cetaceans) as a vessel moves towards the closest point of approach (CPA = 100 m) with a speed of 15 knots. The calculations are based on modelled noise propagation from ultrasonic transducers onboard HAFNIA GALATEA in the Skagerrak. The temporary threshold shift (TTS VHF) for very high-frequency cetaceans is exceeded when the vessel is close to the CPA.**

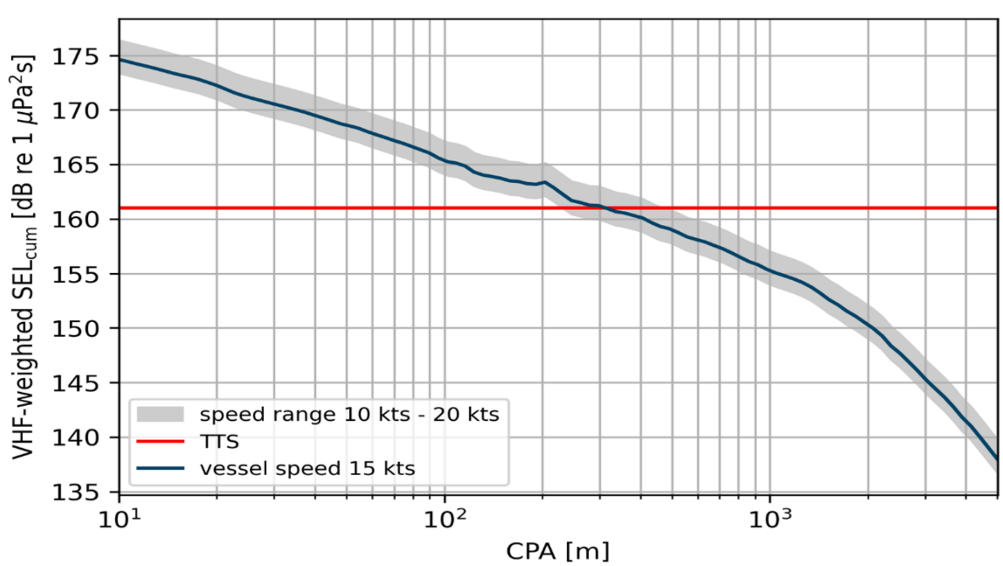

Figure 4.14 **Cumulative sound exposure levels (SEL_{cum}, weighted for very high-frequency cetaceans) in the Singapore Strait resulting from ultrasonic transducers onboard HAFNIA GALATEA as affected by the closest point of approach (CPA). The temporary threshold shift (TTS) for very high-frequency cetaceans is exceeded for CPA-distances up to approx. 500 m dependent on vessel speed.**

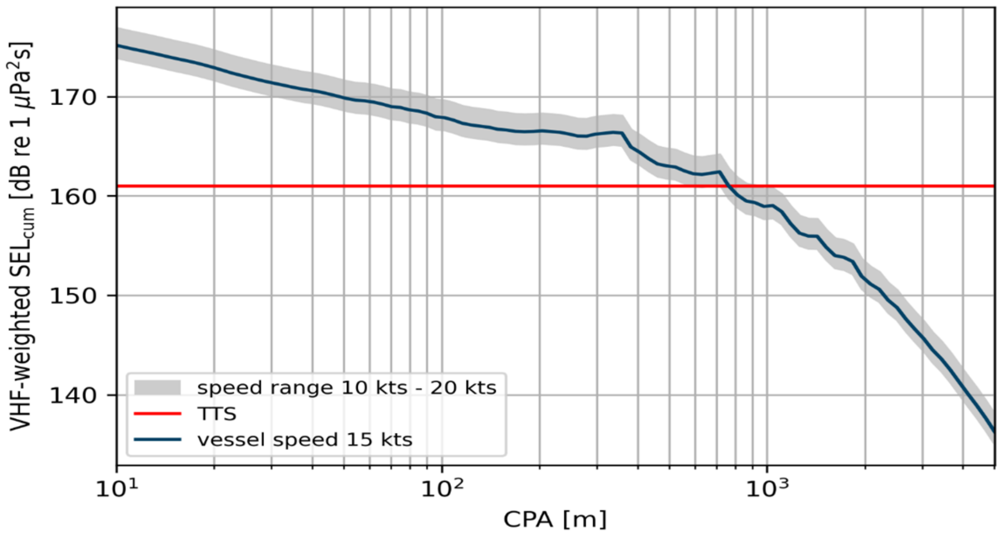

Figure 4.15 Cumulative sound exposure levels (SEL_{cum}, weighted for very high-frequency cetaceans) in the Skagerrak resulting from ultrasonic transducers onboard HAFNIA GALATEA as affected by the closest point of approach (CPA). The temporary threshold shift (TTS) for very high-frequency cetaceans is exceeded for CPA-distances up to approx. 1000 m dependent on vessel speed.

The results of this initial evaluation indicate that underwater radiated noise emitted from ultrasonic antifouling systems may cause adverse effects on the behaviour and hearing ability of cetaceans of which *very high-frequency cetaceans*, such as harbour porpoise, are the most sensitive. To reduce the adverse environmental effects of underwater noise, the shipping industry may consider route planning avoiding feeding or breeding areas for marine mammals (particularly harbour porpoise), habitats populated with endangered species, and other protected or sensitive sea areas.

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Appendix A Sound frequency spectrograms

The measured sound data is available as time domain data representing acoustic pressure fluctuations with time. To differentiate sounds emitted from different sources, carry out an efficient propagation modelling, and finally assess the impact on marine mammals, it is beneficial to analyse the data in the frequency domain. The data is thus transformed to the frequency domain by temporal segmentation and the application of a short time Fourier transform (STFT) to the individual segments. For each time segment this approach yields the power spectral density (PSD) which reflects the distribution of acoustic power within the segment over different frequencies. The multiplication of the time domain signal by windowing functions prior to the transformation may additionally improve the spectral properties of the PSD. When a windowing function is applied, the segments may overlap, and furthermore, if the individual resulting spectra are averaged, the entire process is known as Welch's method which is particularly suited to process longer, stationary and noisy time signals (Welch, 1967).

For each measurement the time domain signal was segmented in snippets of 0.25 seconds, a Hanning window was applied, and the overlap was chosen to zero. The resultant PSD from the STFT may then be plotted as spectrograms as illustrated in Figures A.1 and A.2. The spectrograms visualize how the frequency content of the received acoustic signal changes over time. Figure A.1 shows the resultant spectrogram for a measurement at close distance to EARL 3 with the ultrasonic transducers turned off, while Figure A.2 shows a measurement at the same position with the transducers turned on. The results in Figures A.1 and A.2 are similar up to a frequency of approx. 20 kHz. The high levels (greenish to red colour) with continuous tonal, narrow band components (horizonal lines) below 1000 Hz are typical for vessel noise and machinery like generators and pumps. The engine on the DHI survey vessel was set in neutral gear and thus contributed to the noise, but other vessels may also have contributed as underwater noise can carry over considerable distances and the traffic in the area is very high. Noise at higher frequencies was likely caused by both biological and anthropogenic sources like sonar equipment on nearby vessels.

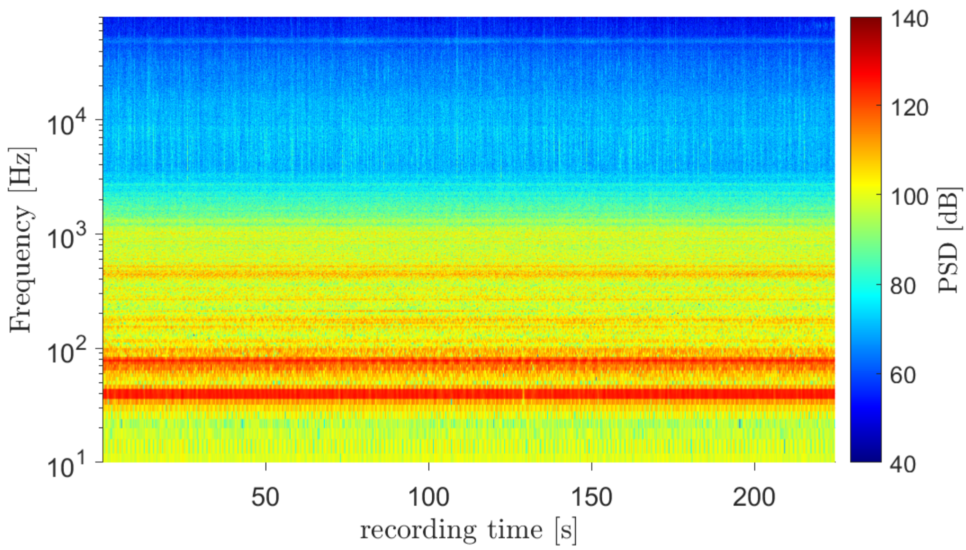

Figure A.1 Power spectral density (PSD) of sound emitted from ultrasonic transducers onboard EARL 3: 20-m distance, 2-m depth, transducers off.

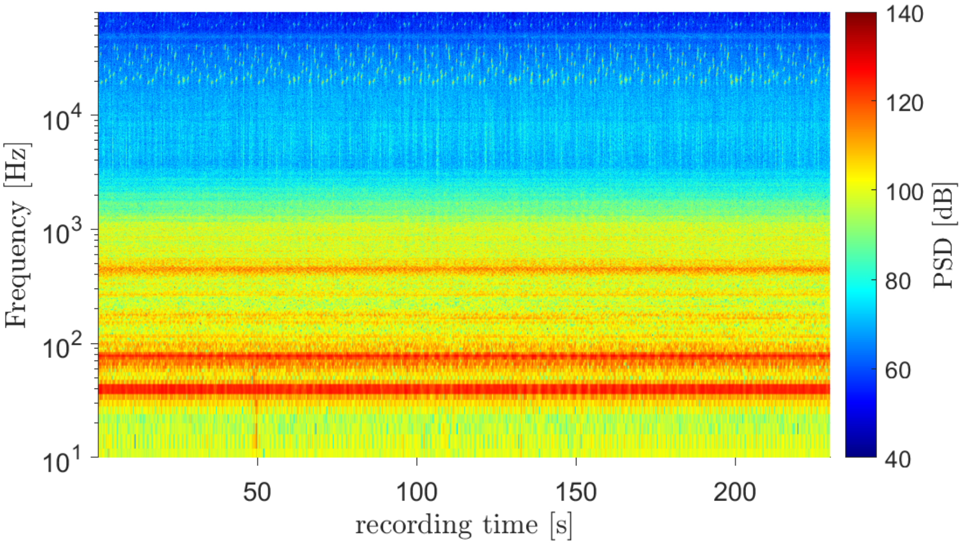

Figure A.2 Power spectral density (PSD) of sound emitted from ultrasonic transducers onboard EARL 3: 20-m distance, 2-m depth, transducers on.

Differences between the two spectrograms in Figures A.1 and A.2 are seen at frequencies above approx. 20 kHz, as the ultrasonic transducers emit short pulses at varying frequencies resulting in a dot-pattern in the spectrogram. Figures A.3 and A.4 show the same data but limited to frequencies above 10 kHz and with an adjusted colour scale showing the signal more clearly. The impulsive and frequency hopping nature of the signal emitted by the ultrasound transducers deviates clearly from the continuous tonal nature of the sounds emitted by antifouling equipment investigated in earlier studies (Martin *et al.*, 2023).

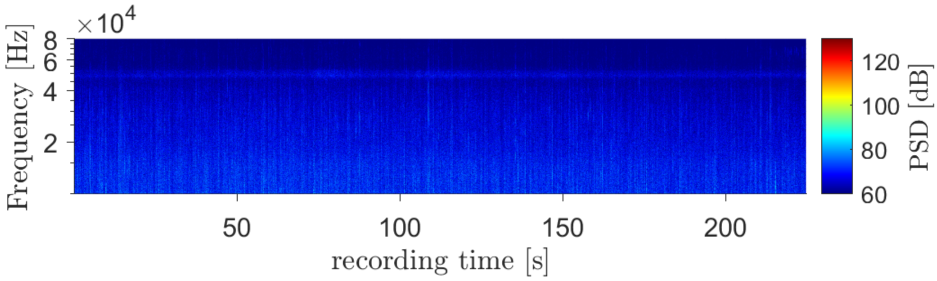

Figure A.3 Power spectral density (PSD) of sound emitted from ultrasonic transducers onboard EARL 3 limited to frequencies >10 kHz: 20-m distance, 2-m depth, transducers off.

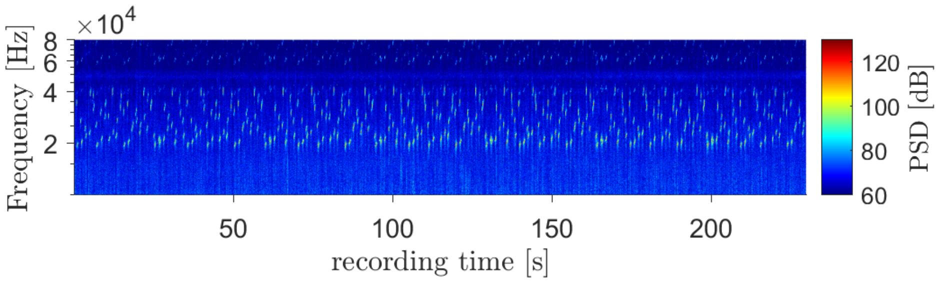

Figure A.4 Power spectral density (PSD) of sound emitted from ultrasonic transducers onboard EARL 3 limited to frequencies >10 kHz: 20-m distance, 2-m depth, transducers on.

While the spectrograms shown above help to understand the nature of the signal and the overall soundscape they are of limited use when it comes to quantifying the source strength and assess potential impacts on marine mammals which is usually based on the sound exposure level (SEL) in 1/3 octave bands. For stationary signals, the sound exposure level over one second (SEL_{1s}) is equivalent to the sound pressure level (SPL). The SPL in 1/3 octave bands is obtained by applying Welch's method (Welch, 1967) and integrating the averaged PSD over the frequencies contained in each 1/3 octave band. The resultant spectra for measurements at close distance to EARL 3 are shown in Figure A.5 (transducers turned off) and Figure A.6 (transducers turned on). Here, the blue line marks the computed mean, the grey area shows the minimum and maximum values of the individual segments, and the black lines indicate their percentiles.

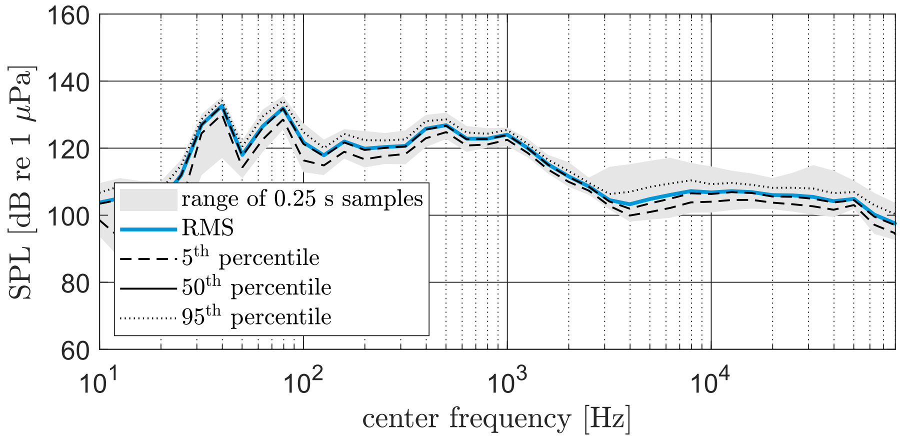

Figure A.5 Sound pressure levels (SPL) for the noise from the ultrasonic transducers onboard EARL 3: 20-m distance, 2-m depth, transducers off (RMS, root mean square).

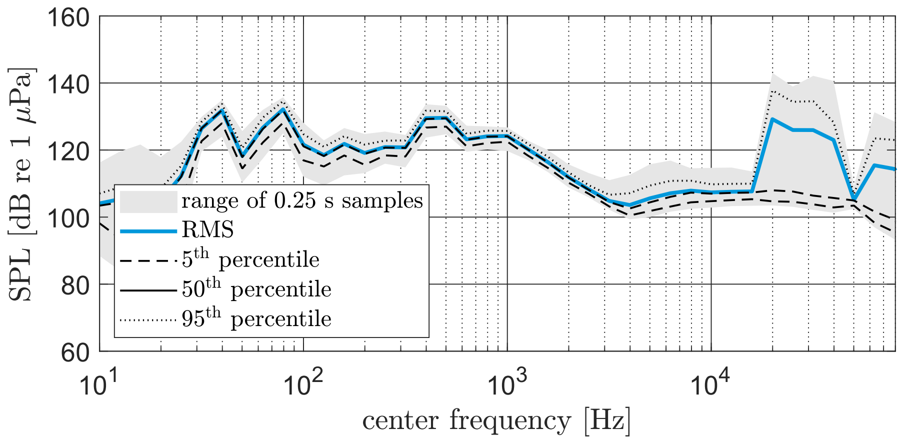

Figure A.6 Sound pressure levels (SPL) for the noise from the ultrasonic transducers onboard EARL 3: 20-m distance, 2-m depth, transducers on (RMS, root mean square).

Figures A.7 to A.9 show the sound pressure levels for HAFNIA GALATEA at 50-meters distance perpendicular to the keel line for three cases: (i) transducers in cooling system and at propeller off (i.e., all transducers off), (ii) transducers in cooling system on and transducers at propeller off, and (iii) transducers in cooling system and at propeller on. Sound was emitted not only within the frequency range of the transducer (approx. 20 kHz to 30 kHz) but also at higher frequencies (>50 kHz). The sound pressure levels decrease with increasing distance, especially for the higher frequencies (Figure A.10).

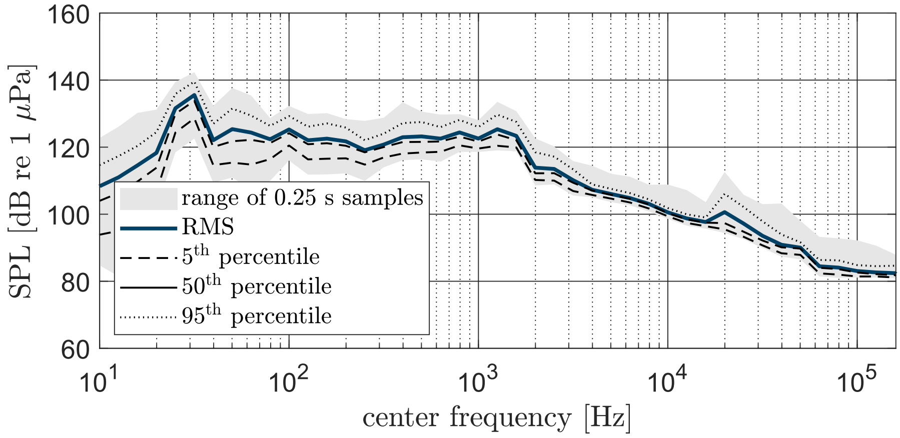

Figure A.7 **Sound pressure levels (SPL) for the noise from the ultrasonic transducers onboard HAFNIA GALATEA: 50-m distance, all transducers off (RMS, root mean square).**

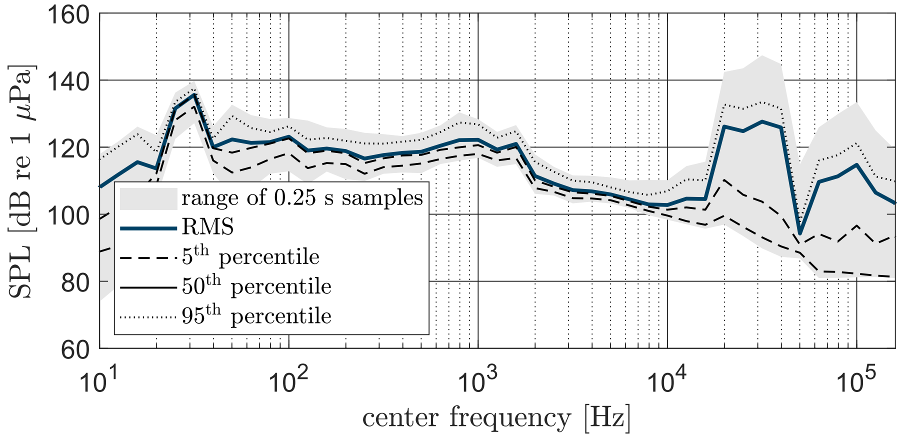

Figure A.8 **Sound pressure levels (SPL) for the noise from the ultrasonic transducers onboard HAFNIA GALATEA: 50-m distance, transducers in cooling system on, transducers at propeller off (RMS, root mean square).**

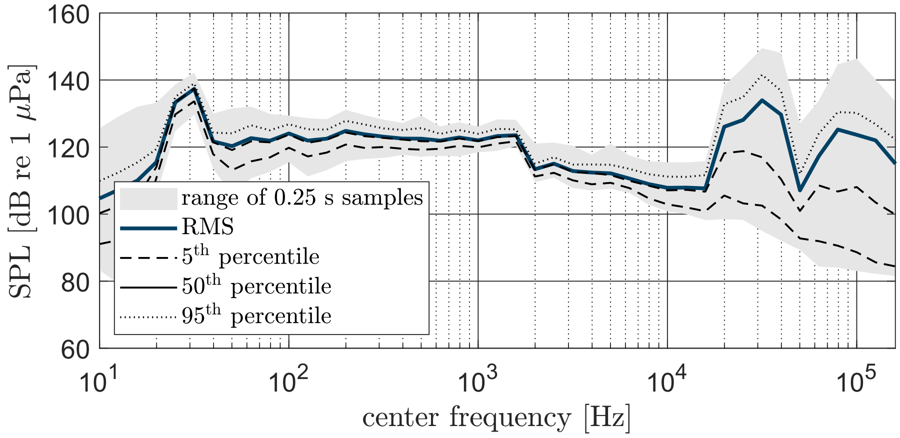

Figure A.9 **Sound pressure levels (SPL) for the noise from the ultrasonic transducers onboard HAFNIA GALATEA: 50-m distance, transducers in cooling system and at propeller on (RMS, root mean square).**

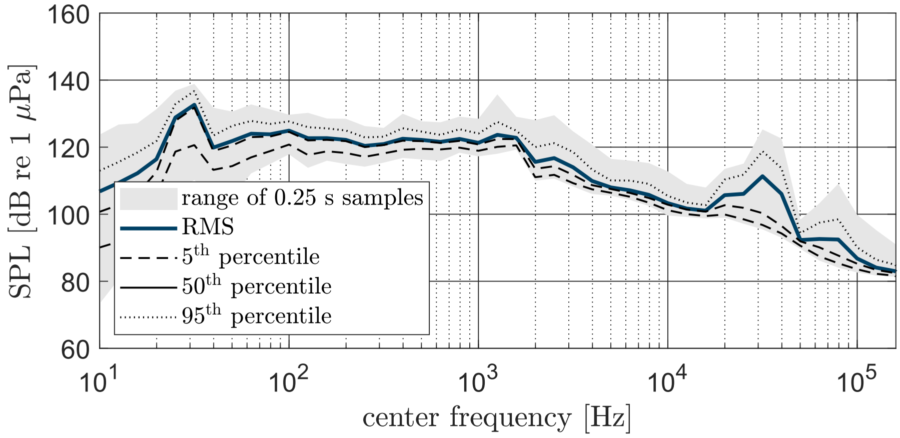

Figure A.10 Sound pressure levels (SPL) for the noise from the ultrasonic transducers onboard HAFNIA GALATEA: 1000-m distance, transducers in cooling system and at propeller on (RMS, root mean square).

To separate the sound generated by the transducers in the cooling system from that generated at the propeller, additional measurements were conducted in the keel line in the aft direction with only the transducers at the propeller on. The measurements were conducted at three distances, and strong currents implied that the measurement vessel drifted during the sound recordings which introduced uncertainty related to the actual distances. An example of the sound recordings is shown in Figure A.11. The emitted sound is clearly detectable even when only the transducers at the propeller were on, but the levels were relatively low compared to those induced by the transducers in the cooling system (see Figure A.8).

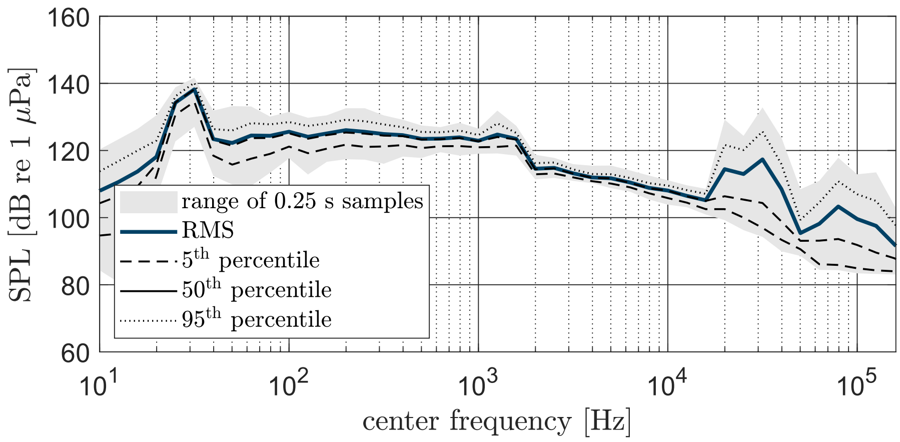

Figure A.11 Sound pressure levels (SPL) for the noise from the ultrasonic transducers onboard HAFNIA GALATEA: 20-m distance, aft direction (uncertain), transducers in cooling system off, transducers at propeller on (RMS, root mean square).

Appendix B Modelling of underwater noise

Appendix B.1 Seabed and water properties

As high frequencies do not penetrate deep into the seabed only a first layer was modelled as an equivalent fluid. The seabed was assumed to consist of sand in all investigated models. Water properties for the Singapore Strait were based on measurements of the first 10 meters of the water column. The resultant properties were all assumed constant over depth as shown in Figure B.1. For the second scenario representing the conditions during winter in the Skagerrak, literature data was used. Data for pH was obtained from the World Ocean Database. The World Ocean Atlas 2023 was selected for the analysis of temperature (Locarnini *et al.* 2024) and salinity (Reagan *et al.* 2024). The temperature and salinity data were converted into a sound velocity profile with a use of the UNESCO equation (Fofonoff and Millard 1983). The resultant profiles are shown in Figure B.2.

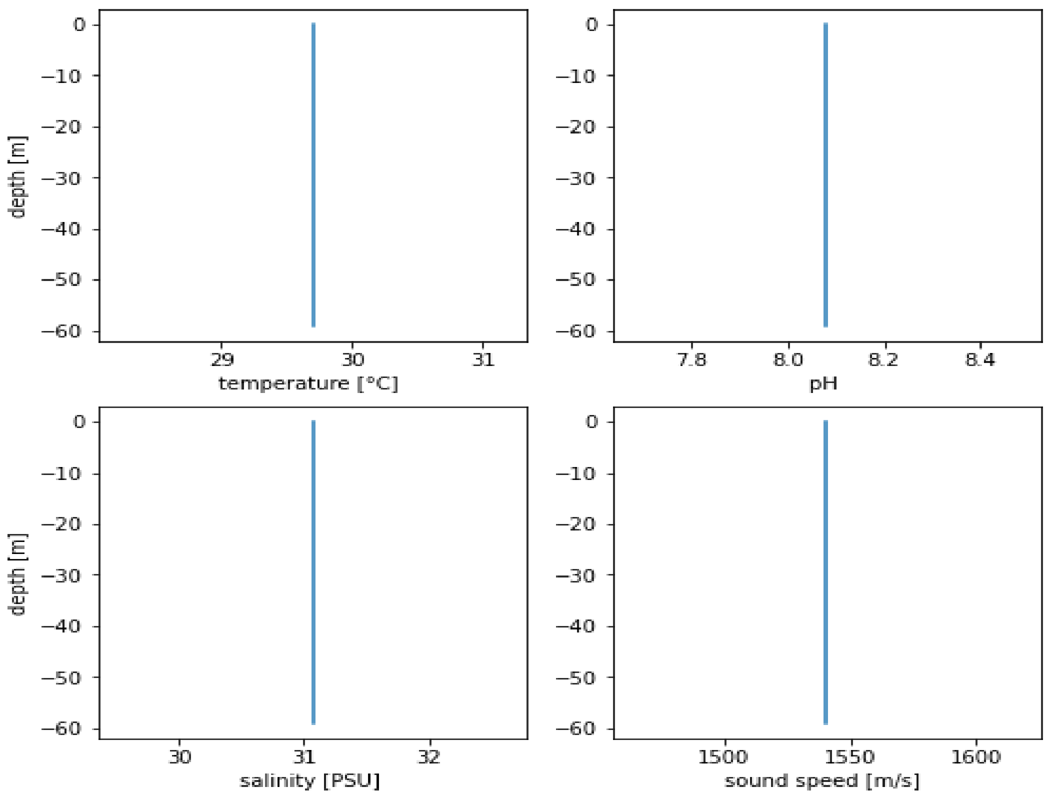

Figure B.1 Water properties assumed for the Singapore Strait.

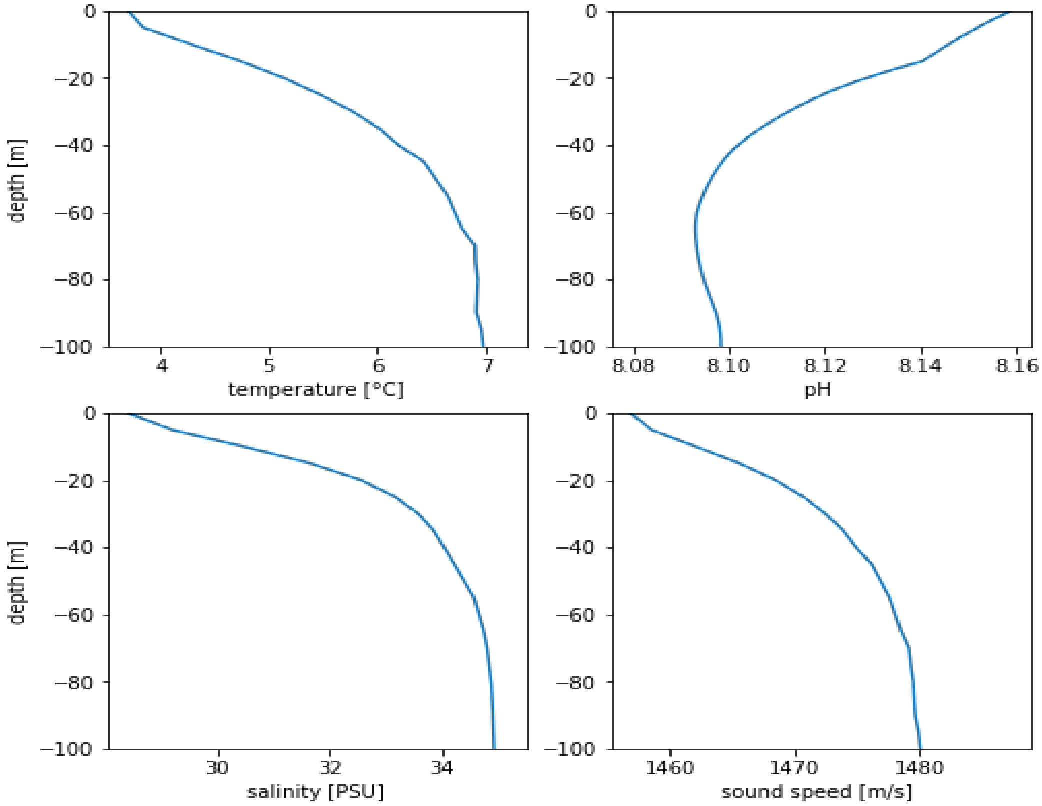

Figure B.2 Water properties assumed for the Skagerrak.

Appendix B.2 Sound pressure levels - HAFNIA GALATEA

Singapore Strait

A single transect of 10 km length with constant water depth was modelled assuming negligible influence of the bathymetry over the relatively short distance. The resulting sound field is shown in Figure B.3.**Error! Reference source not found.**

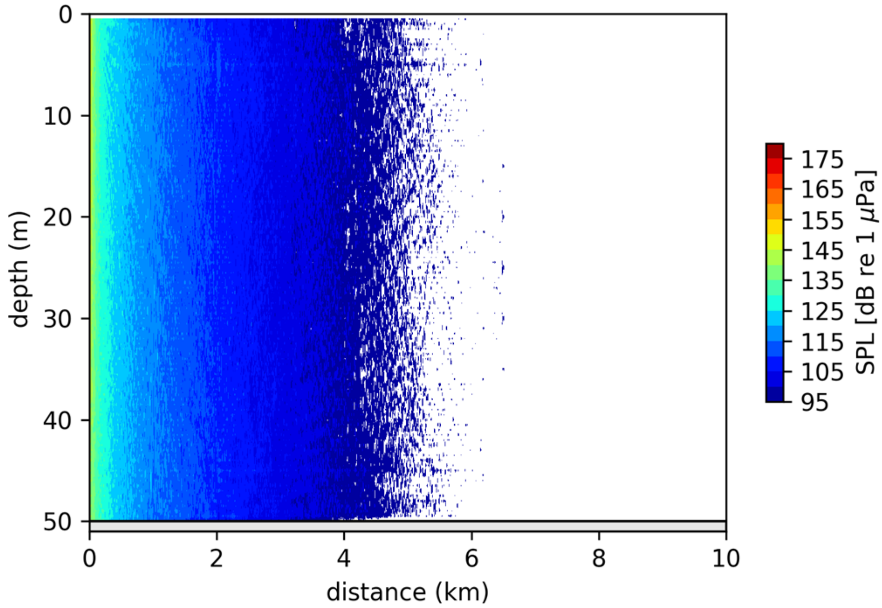

Figure B.3 **Sound pressure level distribution in the modelled transect (20kHz-40kHz) for HAFNIA GALATEA in the Singapore Strait.**

Figures B.4 to B.7 show the modelled and measured sound pressure levels in specific frequency bands over range. The range-averaging described in Section 2.5.3 was applied, and it is seen that the agreement between the measurements and the model is very good.

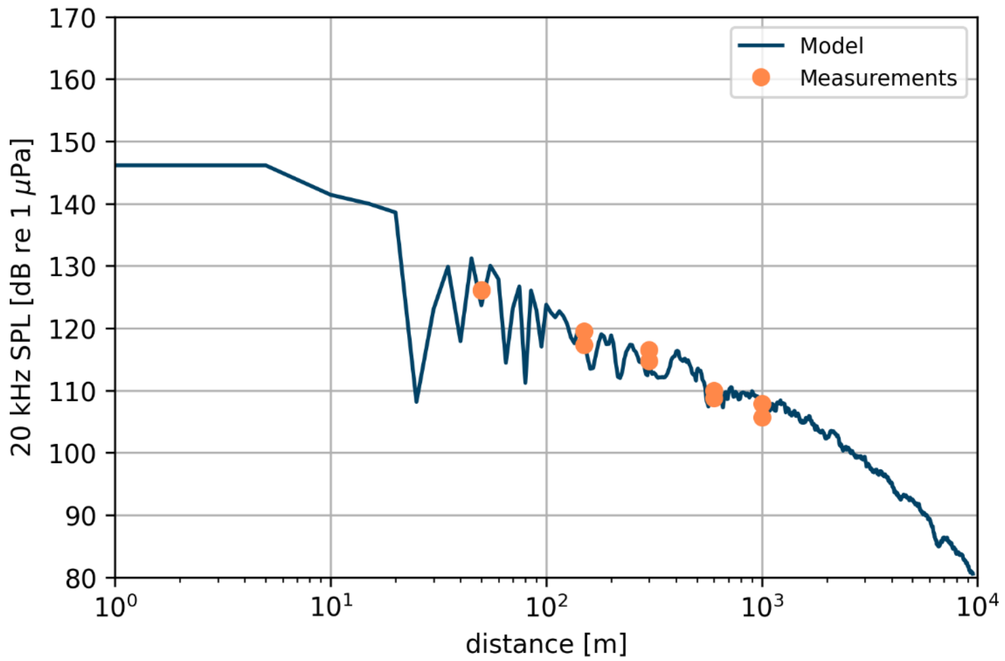

Figure B.4 **Modelled sound pressure levels (SPL) in the Singapore Strait at 5 meters depth in the frequency band centred at 20 kHz compared to measured mean SPL for the noise emitted from the ultrasonic transducers in HAFNIA GALATEA**

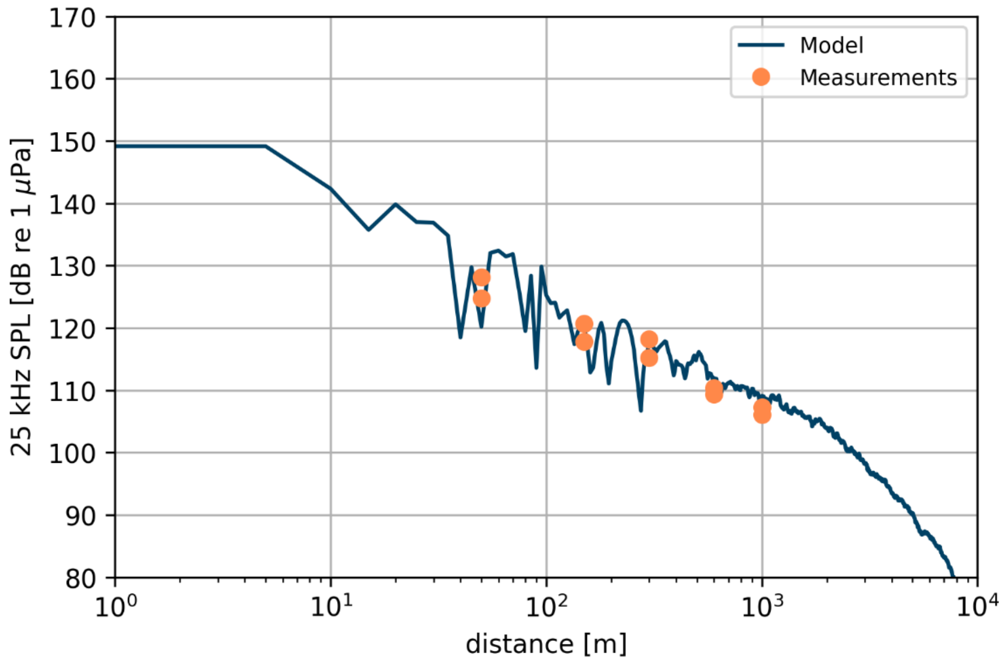

Figure B.5 **Modelled sound pressure levels (SPL) in the Singapore Strait at 5 meters depth in the frequency band centred at 25 kHz compared to measured mean SPL for the noise emitted from the ultrasonic transducers in HAFNIA GALATEA.**

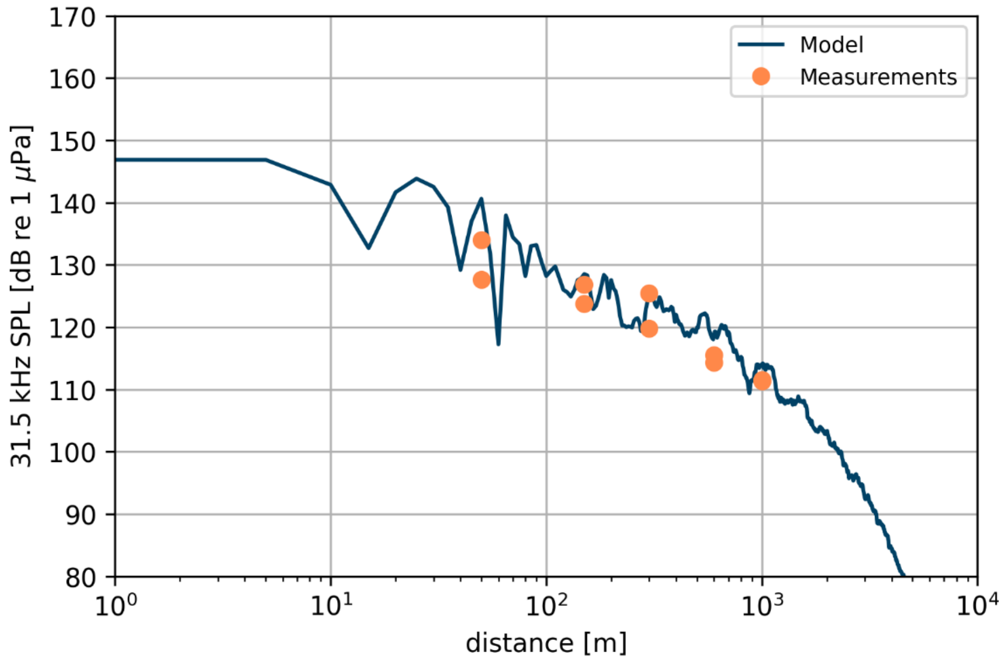

Figure B.6 **Modelled sound pressure levels (SPL) in the Singapore Strait at 5 meters depth in the frequency band centred at 31.5 kHz compared to measured mean SPL for the noise emitted from the ultrasonic transducers in HAFNIA GALATEA.**

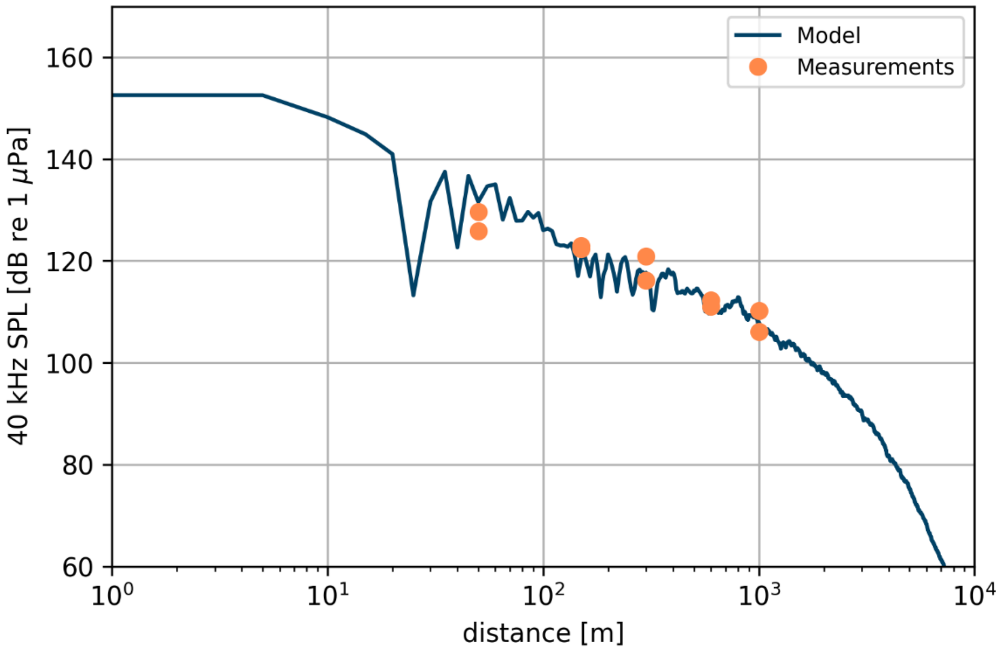

Figure B.7 Modelled sound pressure levels (SPL) in the Singapore Strait at 5 meters depth in the frequency band centred at 40 kHz compared to measured mean SPL for the noise emitted from the ultrasonic transducers in HAFNIA GALATEA.

Skagerrak

The investigated scenario features an upwards refracting sound speed profile resulting in a surface duct. The overall volume attenuation is slightly higher in Skagerrak compared to the properties of the Singapore Strait. This leads to a less efficient sound transmission close to the seabed and increased sound pressure levels in the upper part of the water column as seen in Figure B.8.

No measurements were made in the Skagerrak, and, therefore, the model could not be validated.

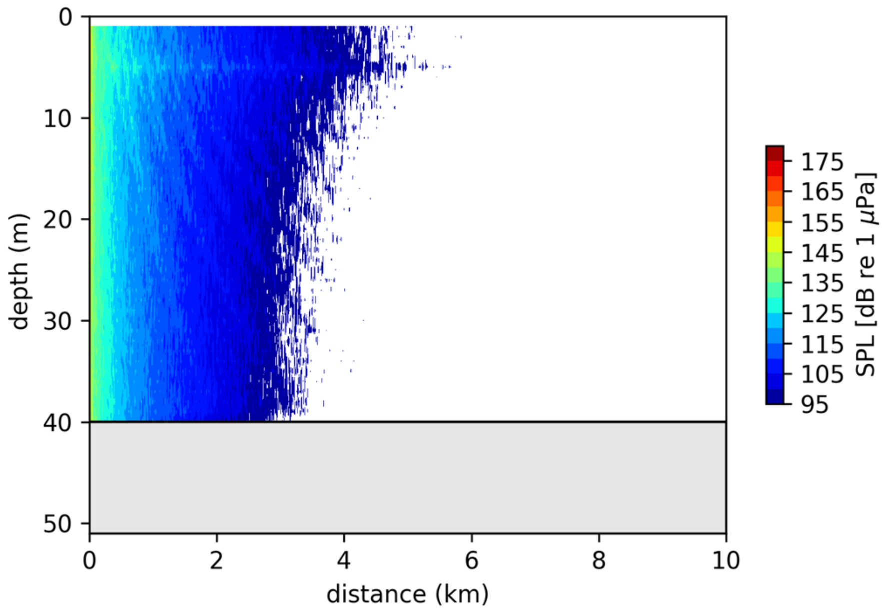

Figure B.8 Sound pressure level distribution in the modelled transect (20kHz-40kHz) for HAFNIA GALATEA for environmental conditions representing the Skagerrak.

Appendix B.3 Sound pressure levels - EARL 3

A single transect of 2 km length with constant water depth was modelled assuming negligible influence of the bathymetry over the relatively short distance. The resulting sound field is shown in Figure B.9.

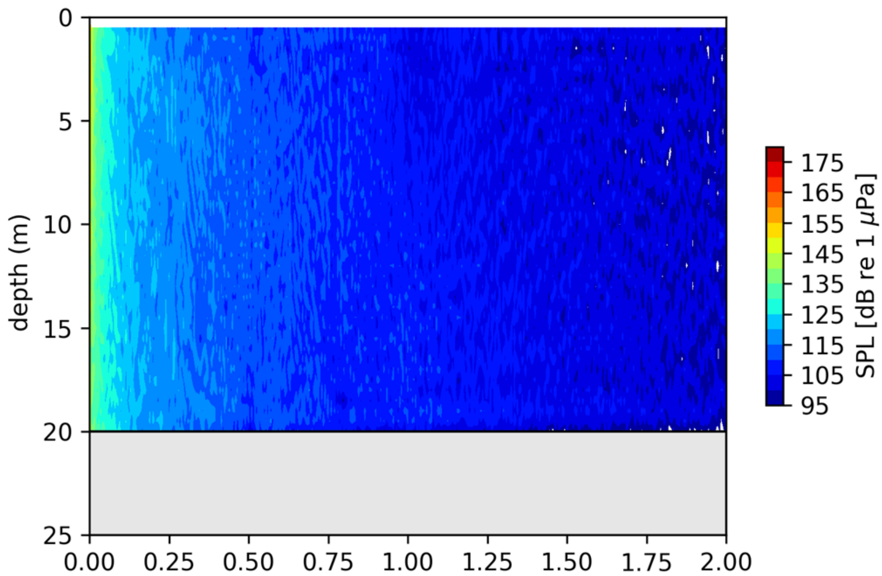

Figure B.9 Sound pressure level distribution in the modelled transect (20kHz-40kHz) for EARL 3.

Figures B.10 to B.13 show the modelled and measured sound pressure levels in specific frequency bands over range. The range-averaging described in Section 2.5.3 was applied, and it is seen that the agreement between the measurements and the model is very good.

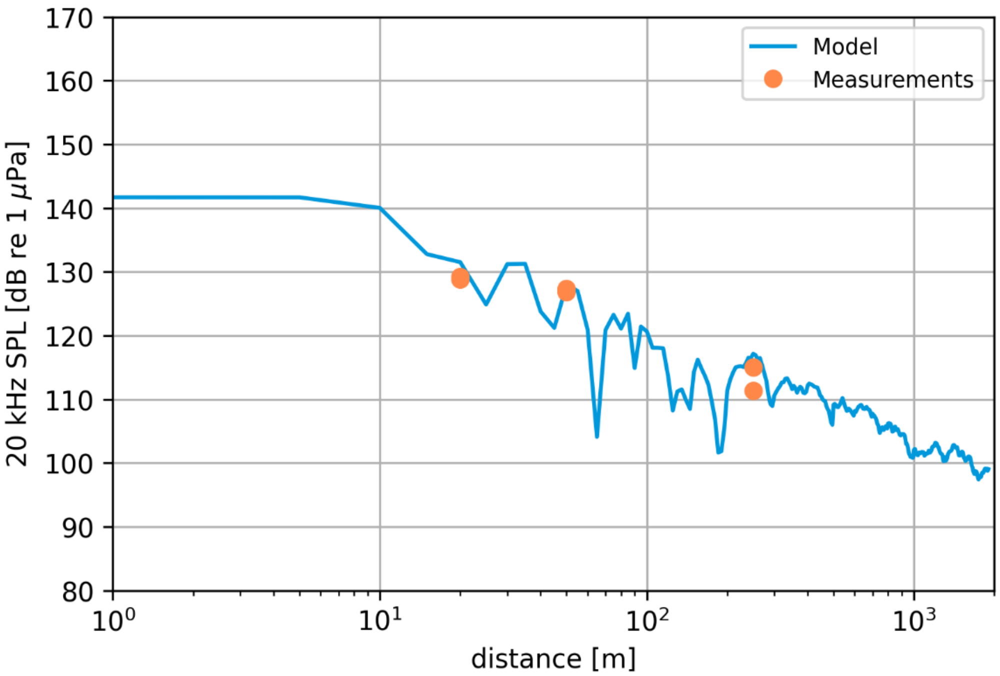

Figure B.10 Modelled sound pressure levels (SPL) in the Singapore Strait at 5 meters depth in the frequency band centred at 20 kHz compared to measured mean SPL for the noise emitted from the ultrasonic transducers in EARL 3.

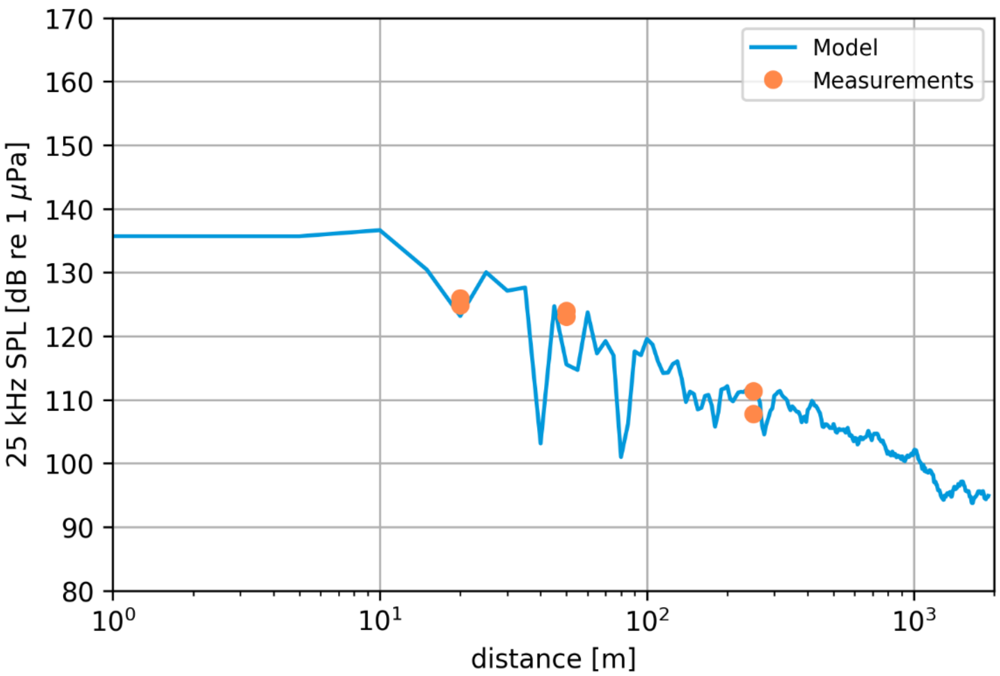

Figure B.11 Modelled sound pressure levels (SPL) in the Singapore Strait at 5 meters depth in the frequency band centred at 25 kHz compared to measured mean SPL for the noise emitted from the ultrasonic transducers in EARL 3.

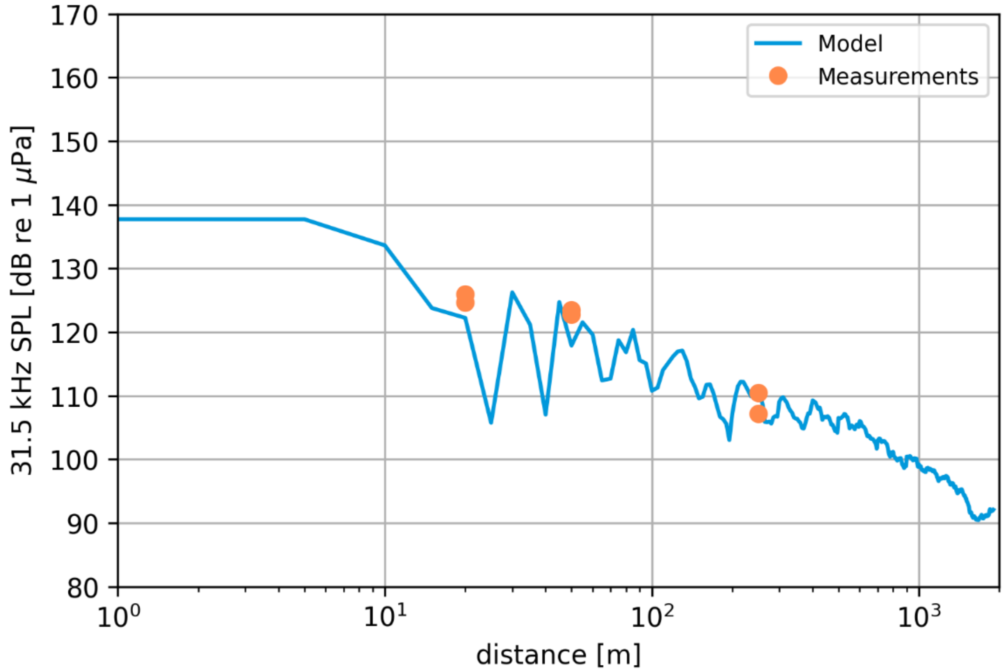

Figure B.12 Modelled sound pressure levels (SPL) in the Singapore Strait at 5 meters depth in the frequency band centred at 31.5 kHz compared to measured mean SPL for the noise emitted from the ultrasonic transducers in EARL 3.

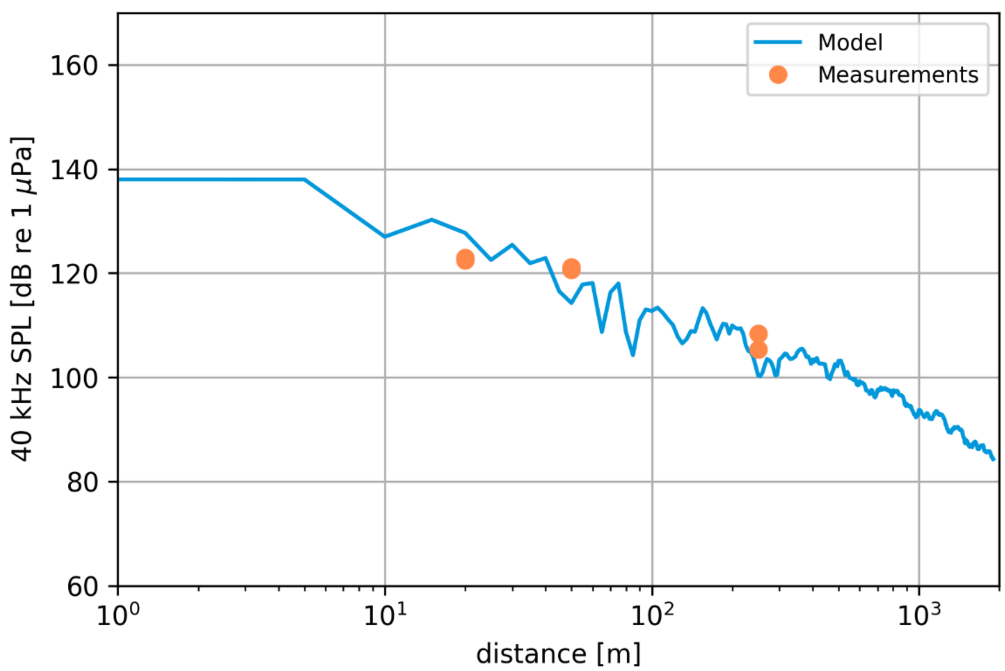

Figure B.13 Modelled sound pressure levels (SPL) in the Singapore Strait at 5 meters depth in the frequency band centred at 40 kHz compared to measured mean SPL for the noise emitted from the ultrasonic transducers in EARL 3.

Appendix C Biological impact assessment

Appendix C.1 Sound levels of continuous noise

Continuous noise is generally described with the sound pressure level (SPL). An important aspect in the evaluation of the SPL is the considered time window T_0. Usually, statistical evaluations of the measured SPL with the consideration of 1-second windows are provided in ambient noise studies.

$$\mathrm{SPL} = 10\log_{10}\left(\int_{t_{\mathrm{start}}}^{t_{\mathrm{end}}} \frac{p^2(t)}{T_0 E_{p0}} \mathrm{d}t\right) \quad \text{with} \quad p_0 = 1\ \mu\mathrm{Pa}$$

The cumulated sound exposure level ($\mathrm{SEL}_{\mathrm{cum}}$) represents the total acoustical dose received by the exposed animal. $\mathrm{SEL}_{\mathrm{cum}}$ is derived by cumulating the acoustic energy of the 1-second time window (SPL) over the expected duration of the continuous noise (T_{cont} in seconds):

$$\mathrm{SEL}_{\mathrm{cum}} = \mathrm{SPL} + 10\log_{10}(T_{\mathrm{cont}})$$

Appendix C.2 Functional hearing groups and weighting approach

Marine mammals are divided into functional hearing groups based on the way they perceive sound. Different hearing characteristics related to the range of sounds, a particular group of animals perceives, were compared by the National Marine Fisheries Service (NMFS 2018, 2024; Southall *et al.* 2007) with the use of frequency weighting expressed as:

$$W(f) = C + 10\log_{10}\left(\frac{(f/f_1)^{2a}}{\left[1 + (f/f_1)^2\right]^a \left[1 + (f/f_2)^2\right]^b}\right)$$

where $W(f)$ is the weighting function amplitude (in dB) at the frequency f (in kHz), and the parameters *a, b* and *C* and the frequencies f_1 and f_2 are presented in Table C.1. The corresponding weighting curves are presented in Figure C.1. For each hearing group, the parameters in the auditory weighting function were derived from available data on the hearing sensitivity of the groups (NMFS, 2024).

The generalized hearing ranges for the functional hearing groups are presented in the main report Table 2.2.

Table C.1 Functional hearing groups and parameters used for frequency weighting.

Functional Hearing Groups	a	b	f_1 [kHz]	f_2 [kHz]	C [dB]
Very high-frequency (VHF) cetaceans (2)	1.8	2	12	140	1.36
Low-frequency (LF) cetaceans (1)	0.99	5	0.168	26.6	0.12
High-frequency (HF) cetaceans (1)	1.55	5	1.73	129	0.32
Very high-frequency (VHF) cetaceans (1)	2.23	5	5.93	186	0.91

References: (1) NMFS, 2024; (2) Southall *et al.* 2019

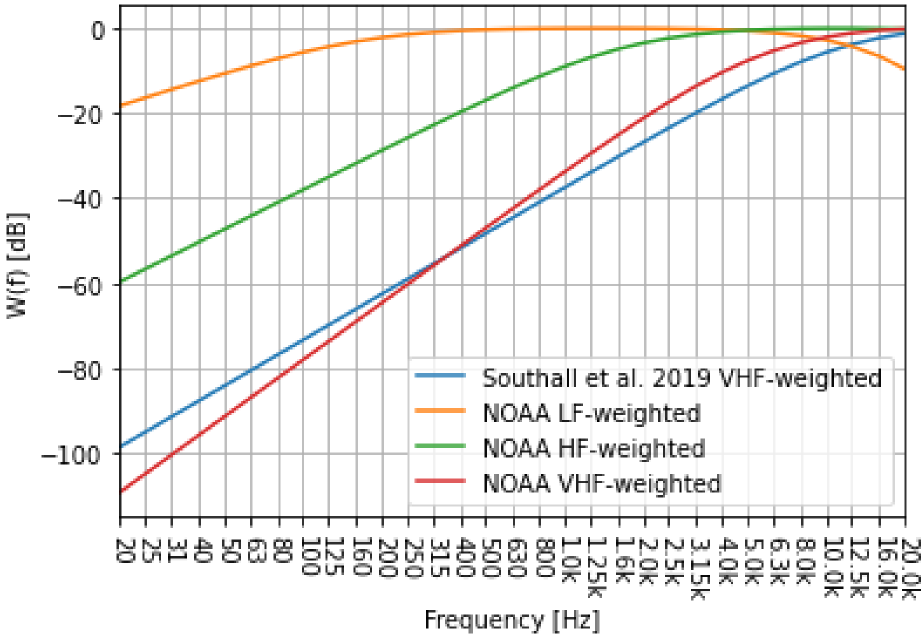

Figure C.1 Comparison of weighting functions for cetacean hearing groups.

Notes: NOAA, The National Oceanic and Atmospheric Administration; LF, low-frequency cetaceans; HF, high-frequency cetaceans; VHF, very high-frequency cetaceans.

Appendix C.3 Adjusting for complex sound

The effects of sound exposure on the marine fauna depend not only on the levels, frequency content, and duration of the of the received dose but also on the type of sound. Hence, thresholds are often defined for two different categories of sound: Continuous sound like vessel noise and impulsive sound like the sound generated from percussive pile driving. This simple categorization is reaching its limit when the sound is not easily classified as either continuous or impulsive. Sound that possesses characteristics of both categories is referred to as complex sound. The sound emitted by the investigated ultrasonic transducers falls under this category (Figure A.4).

One measure to quantify the impulsiveness of a given sound signal is the kurtosis β of the signal where $\beta = 3$ holds true for continuous Gaussian white noise and $\beta > 40$ for purely impulsive sounds. A recent proposition to adjust the computed sound exposure levels based on the signals kurtosis was adopted to account for the signal characteristics (Lucke *et al.*, 2024). This approach relies on kurtosis-based adjustment factors for each hearing group and evaluating the adjusted sound exposure levels SEL_w against the thresholds for continuous sounds.

The required adjustment A_{cs} is computed from

$$SEL_w = SEL_w + \underbrace{\lambda \log_{10} \frac{\beta}{3}}_{A_{cs}}$$

Where the scaling parameter λ can be derived from the difference in the thresholds for continuous and impulsive noise.

The kurtosis β can be computed from the time domain pressure signal $p(t)$ as described by Müller *et al.* (2020):

$$\beta = (t_1 - t_0) \frac{\int_{t_0}^{t_1} p(t)^4 \, \mathrm{d}t}{\left(\int_{t_0}^{t_1} p(t)^2 \, \mathrm{d}t\right)^2}.$$

During travelling, multiple sound sources such as engine, flow and cavitation noise contribute to the broadband noise emitted from a vessel and affect both the sound levels and its kurtosis. Within this study, however, the effect of the ultrasound transducers is investigated isolated from other sources, and the time domain signal was filtered using a second order high pass Butterworth filter with a cut of frequency of 10 kHz before computing the kurtosis of the signal. This process resulted in values within the range of $\beta \approx 10 \ldots 20$ for all recordings where the transducers were operational, and thus $\beta = 15$ was assumed for the determination of the adjustment factors. The above considerations eventually yield the adjustment factors listed in Table C.2.

Table C.2 Adjustment for complex sound considering temporary threshold shift and auditory injury assuming kurtosis $\beta = 15$.

Hearing Group	Adjustment, A_{cs} [dB]
Low-frequency cetaceans	8.7
High-frequency cetaceans	5.0
Very high-frequency cetaceans	13.7

Reference: NMFS, 2024.

Appendix C.4 Thresholds for noise impact

Thresholds for noise impact are commonly defined for either impulsive or continuous sound. However, the classification is not always unambiguous. For cumulative sound exposure levels, the previously described kurtosis-based adjustment is performed. Since this is not feasible for the behavioural thresholds based on sound pressure levels, the sound was assumed continuous following available definitions (van der Graaf et *al.*, 2012). The application of the behavioural threshold for very high-frequency cetaceans (Tougaard, 2021) represents a deviation from this assumption, as it was derived from observations during pile driving events that are clearly impulsive. Tougaard (2021) indicates that the threshold is likely applicable for different sound types, and such broader use has been practiced in previous studies (Martin et *al.*, 2023).

Appendix C.5 Effect of exposure time

To obtain a better understanding of how exposure duration affects the impact ranges, Figures C.2 to C.4 illustrate the exposure durations that would be required to reach each of the respective thresholds if the distance is kept constant for the entire time.

Taking the data for the ultrasonic transducers onboard HAFNIA GALATEA as example, it is seen that:

- An exposure duration of 100 seconds may cause *temporary threshold shift for very high-frequency cetaceans* at distances up to approx. 300 m in the Singapore Strait (Figure C.2) and up to approx. 500 m in the Skagerrak (Figure C.3)

- An exposure duration of 100 seconds may cause *auditory injury for very high-frequency cetaceans* at distances up to approx. 15 m in the Singapore Strait (Figure C.2) and the Skagerrak (Figure C.3).

Temporary threshold shift and auditory injury for low-frequency and high-frequency cetaceans require either close distance to the sound source or long exposure duration (Figures C.2 and C.3).

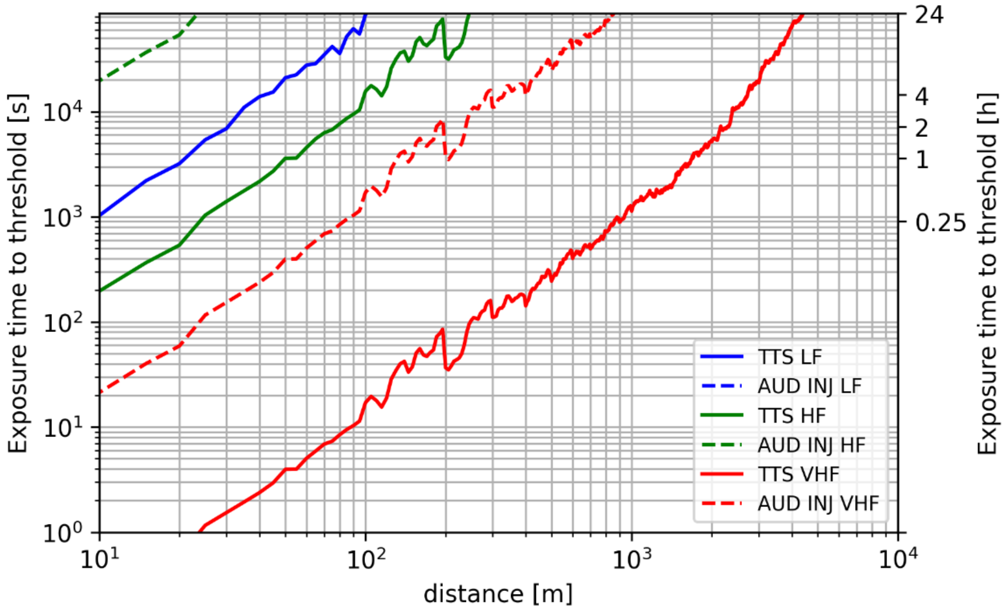

Figure C.2 Hearing impact thresholds as function of distance and exposure time. Modelled data for noise from ultrasonic transducers onboard HAFNIA GALATEA in the Singapore Strait.
Notes: TTS, temporary threshold shift; AUD INJ, auditory injury; LF, low-frequency cetaceans; HF, high-frequency cetaceans; VHF, very high-frequency cetaceans.

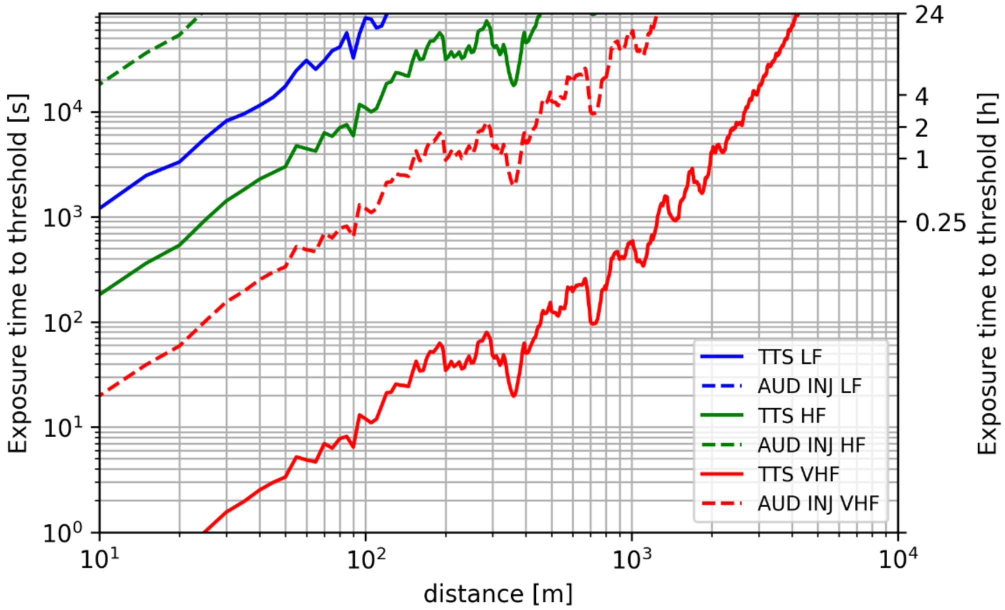

Figure C.3 Hearing impact thresholds as function of distance and exposure time. Modelled data for noise from ultrasonic transducers onboard HAFNIA GALATEA in the Skagerrak.
Notes: TTS, temporary threshold shift; AUD INJ, auditory injury; LF, low-frequency cetaceans; HF, high-frequency cetaceans; VHF, very high-frequency cetaceans.

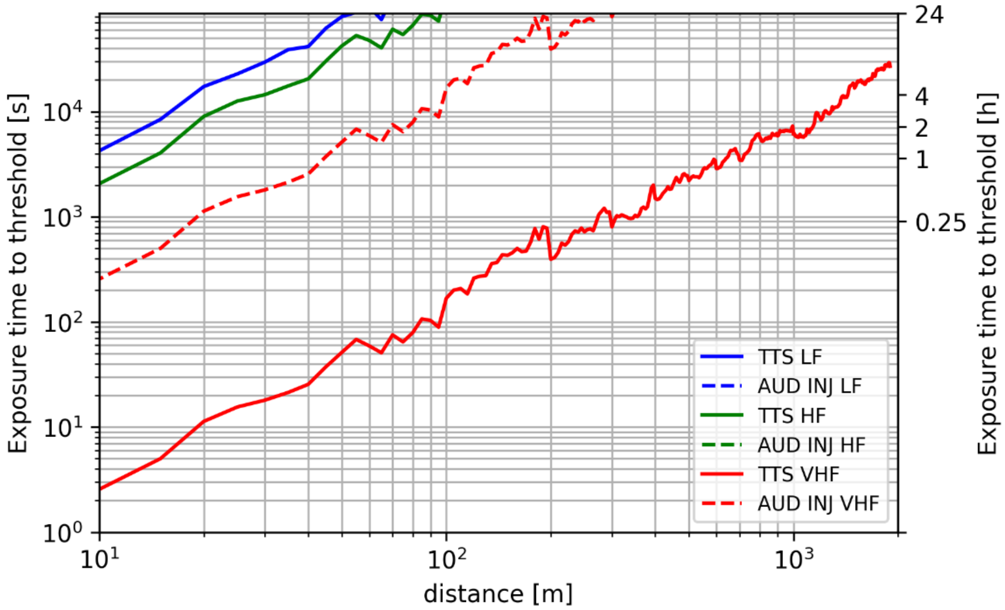

Figure C.4 Hearing impact thresholds as function of distance and exposure time. Modelled data for noise from ultrasonic transducers onboard EARL 3 in the Singapore Strait.
Notes: TTS, temporary threshold shift; AUD INJ, auditory injury; LF, low-frequency cetaceans; HF, high-frequency cetaceans; VHF, very high-frequency cetaceans.