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A Study of Radiated Noise From Fishing Vessels

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Problem description

The scope of this study is to analyze self-noise radiated of large fishing vessels. The motivation is the suspicion the noise radiated from some vessel may cause scaring effects leading to reduced catches. Noise recordings from the vessels have been recorded by the company Ecoxy AS, and made available for use in this master thesis. After a brief summary of pertinent acoustic theory and hearing sensitivity of fish, the thesis should deal with issues such as, but not necessarily limited to:

- Radiated sound levels and frequency distributions spectrum of the recorded noise and analysis and discussion of possible sources of this noise in relation to the design of vessels and the propulsion system. Effects of towing a trawl
- Sound propagation effects and the sound level dependence of distance from vessel to measurement site and directions
- Design a graphical computer interface to facilitates selection of records cases and comparing the results

Abstract

The oceans are covering most of the earth. The noise levels in the oceans are high, even though most people are ignorant to the fact. Through the increase in anthropogenic noise in the oceans, the ambient noise level is rising. Low-frequency sound can propagate over large distances, and is therefore omnipresent. This is the cause of the concern that humans pollute the oceans not only with plastic and rubbish, but pollute with oceanic sound emissions as well. This has, to a large extent unknown consequences for marine life.

There are several anthropogenic noise sources that contribute to the increase of the ambient sound level. The shipping industry together with seismic explorations are two of those that have the largest impact. Seismic explorations have excessive noise levels, but relative to ships, they are rare. Ships on the other hand yield lower noise levels, but are outnumbering the seismic explorations. The emitted noise can harm, disturb and confuse marine life. The literature is more focused on marine mammals, such as wales. However, fish are also affected.

This study focuses on analysis of ship noise. DNV-GL has put forward a standard related to ship noise with specific noise levels that are acceptable for different kinds of ships in different conditions. Ecoxy in collaboration with Jens Hovem have developed a measurement procedure and EcoNoise, a computer program that enables processing of the recorded files with a given structure following a procedure according to this standard. Data from several field trials of measuring fishing vessels conducted by Ecoxy AS were made available for this thesis. The acoustic data which has been processed as part of this thesis stems from these measurements.

EcoNoise, the computer program, has been the basis of the data analysis which will be presented in this thesis. The functions have been changed to find the wanted metrics used for analysis. Different components of the acoustic emissions have been studied, such as the audible range of the noise for fish radiated from the ships as well as suggesting a possible procedure to measure the directivity of the vessels.

A graphical user interface has also been developed for EcoNoise as a part of this thesis. The interface combines all the functionality of EcoNoise in an interface which is easy to use. This has been done to make the program more user friendly and make it more available for people without too much programming knowledge. This is important to enable for example the fishermen themselves to use the program while at sea.

Vibration measurements of the hull of the ferry MF Glutra have been performed. This was done as preparation for measuring the vibration of the hull of one of the fishing vessels, but these measurements were not done due to the ship's schedule. Through established formulae for calculating vibration, the vibration in plates with different characteristics was calculated. Through these simulations, it was found

that the plates have resonance frequencies in the audible range for fish, and will therefore have an impact on fish.

Sammendrag

Havene dekker majoriteten av jordens overflate. Støynivåene i havene er høye, likevel er det lav bevissthet rundt dette temaet. Støynivåene stiger videre på grunn av en økning av menneskeskapt støy i havet. Lavfrekvent lyd kan propagere over store distanser og dempes lite, og er derfor tilstede overalt. Dette er grunnlaget for den urovekkende trenden at menneskene forurenser ikke havene bare med plastikk og annet søppel, men forurenser havene med akustiske lydutslipp også. Konsekvensene lydnivåene har for marint liv er et felt det er viktig å forske videre på.

Det er flere menneskeskapte lydkilder som bidrar til økningen av bakgrunnsstøyen i havene. Skipsindustrien sammen med seismiske undersøk-elser er to av de største bidragsyterne til det økte lydnivået. Seismiske undersøkelser har veldig høye lydnivåer, men er ikke like utbredt som skipstrafikken. Skipene har lavere lydutslipp, men er i gjengjeld mer tilstedeværende. Lyden som genereres kan skade, forstyrre og forvirre marint liv. Litteraturen fokuserer mer på marine pattedyr, som for eksempel hvaler, men fisk påvirkes også.

Denne oppgaven fokuserer på analyse av skipsstøy. DNV-GL har publisert en standard med tilhørende regelverk som setter grenser for lydnivåene som ulike skipstyper kan slippe ut. Ecoxy i samarbeid med Jens Hovem har utviklet en måleprosedyre og EcoNoise, et dataprogram som prosesserer målefilene i henhold til DNV-GLs standard. Data fra målinger av flere fiskefartøy utført av Ecoxy er gjort tilgjengelig for gjennomføringen av denne oppgaven. EcoNoise, dataprogrammet, har vært grunnlaget for dataanalysen som blir presentert i denne oppgaven. Programmets funksjonalitet har blitt endret for å muliggjøre uthentingen av de ønskede dataene. Ulike aspekter ved skipsstøyen har vært sett på, blant annet den avstanden der lyden blir hørbar for fisk, og også et forslag til hvordan man ved hjelp av måleprosedyren kan finne direktiviteten til støyen skipene genererer.

Et grafisk brukergrensesnitt for EcoNoise er blitt utviklet. Grensesnittet kombinerer funksjonaliteten av de ulike delene av EcoNoise på en måte som gjør det enkelt i bruk. Dette er blitt gjort for å gjøre programmet mer brukervennlig og mer tilgjengelig for brukere uten programmeringskunnskap. Dette er et viktig for å gjøre det brukbart for fiskerne selv når de er til havs.

Vibrasjonsmålinger av skroget til fergen MF Glutra er gjennomført. Dette var en del av forberedelsene til å måle vibrasjonene i skroget på et av fiskefartøyene, disse målingene ble dessverre ikke utført på grunn av fartøyets tidsplan. Ved hjelp av formler hentet fra litteraturen ble vibrasjoner i plater med ulike egenskaper simulert og sammenlignet. Det ble funnet at platene har resonansfrekvenser i det hørbare frekvensområdet for fisk og vil derfor ha påvirkning på fisk.

Acknowledgements

This report was carried out by Øystein Solheim Pettersen as part of the Master of Technology study at Norwegian University of Science and Technology (NTNU). The study consists of analysis of data collected through measurements of fishing vessels, as well as making a graphical user interface for EcoNoise and measuring the vibration of the hull of a ferry. I would like to thank my supervisors, Professor Jens Hovem and Professor Hefeng Dong for their help, support and contributions throughout the study.

Øystein Solheim Pettersen

Gløshaugen, June 13, 2017

Contents

1. Introduction

> ...it is probably equally true that no useful mechanical process can occur without generating some vibration and therefore at least a little noise
>
> *Donald Ross*
> *Mechanics of Underwater Sound*

Underwater noise is a broad topic. The sound propagation is a large topic in itself, and there are many different noise sources that contribute to the overall noise level, both biologic and anthropogenic (man made). Each noise source can be studied deeply for itself, but this thesis will focus on acoustical noise generated by ships, and more specifically data analysis and characterization of the radiated noise from fishing vessels.

As stated in the quote above, noise is unavoidable in any meaningful mechanical process, this holds also for the fishing vessels concerned. However, the goal should be to limit, or to change the characteristics of the radiated noise of the vessel so that the vessels acoustic environmental footprint may be minimized. This could be to for example change physical parameters to change the harmonics of the radiated noise or to do preventive measures to restrain the level of the noise. If a ship has excessive radiation at certain frequencies where the hearing capabilities of the fish are good, by changing the frequency of the peak, this part of the ship emitted noise might become inaudible to the fish.

1.1. Background

The interest in anthropogenic underwater noise sources is increasing. The effects the generated noise might have on marine life have long been ignored or been overlooked. This is because of ignorance within the subject of hearing capabilities of fish and marine mammals, and the influence noise might have on these species. However, cases such as whale beaching in areas with seismic activity the issue of underwater noise emissions has been brought to attention. The effects the noise have on fish is still largely unknown. However, first hand reports say that the catches of fish are influenced by the environmental conditions in the area, such as the noise level.

The shipping industry is the largest contributor to the oceanic background noise level. This is due to the large number of vessels and their prevalence on the world seas. The merchant fleet accounts for most ships, but the issue is also relevant to fishing vessels, and for these vessels it also has detrimental implications if the vessel is noisy. If the sound radiated has a high level in the frequency bands where the target species has good hearing capabilities it can result in lower fishing yields.

It is desirable to gain more insight into the underwater acoustic emissions of ships. This can be helpful when diagnosing a ship which might have an inefficient mechanical process, which can show itself in an increased sound level in certain frequency bands or experiencing diminishing catches. If the ship is too noisy it can be disturbing to the surrounding marine life. When this is the case, it is possible to take measures for reducing the radiated noise.

1.2. Literature review

Hovem's Marine Acoustics [6] gives a broad introduction to marine acoustics. Here many different phenomena important for the propagation of sound in water are covered. For an introduction to ship noise, Donald Ross' work [20] goes deep into to the field of underwater sound radiated from ships, as well as also discussing vibration in ship structures. For more specific factors and real measurement data, [13] looks extensively at different commercial ships and their noise level in general, while [1] gives an accurate account of the radiated noise of one specific ship and describes the directivity of the radiated noise of from the ship. Jenssen [9] discusses the numerical simulations approach to ship noise, among other things the directivity of noise from the propeller is looked at. Vibration measurements of a ship hull were also performed, this work was motivating for performing the vibration measurements in this thesis.

Vibration of plates is a well discussed field of research, and it is an important part of the discussion when assessing acoustic phenomena. [11] gives in depth insight to this field. For the calculations performed in this thesis formulas given in [24] were used, in this book a more practical approach is taken from the point of view of building acoustics.

An important reason for doing research in the field of anthropogenic noise sources and ship noise specifically is the rising ambient noise level in the oceans. Interesting correlations are given in [4], where the relationship between the global economy and the noise level in the oceans is described. Ross [21] also describes the rising noise level in the ocean and ties it directly to the total amount of horsepower at sea. The article concludes that the rise in noise level cannot be explained by the increased number of seagoing vessels alone, due to an intrinsic change in the propulsion systems that are being developed and put into use.

The rise of the ambient noise level is mainly worrying because of the impact it has on marine life. The number of species of fish is vast, but in their hearing capabilities there are similarities. A good introduction to the functionality and how different hearing capabilities should be referred to is discussed in [18]. Damage that can be inflicted physically were found in [12], the damage was a result of exposure to excessive sound levels. In [10], it was shown that the sound levels in areas with spawning cod are increasing in certain frequency bands. A suggestion that can be given regarding this is that anthropogenic noise sources will mask the communication signals, harming marine life by denying communication in relation to for example mating.

1.3. Structure of Report

This report consists of eight chapters. Chapter 1 introduces the topic that will be discussed and why it is an important topic in the fishing and ship industry. Chapter 2 describes the necessary theory that is needed to explain the effects that will become evident later in the report. Chapter 3 describes ship noise, which is the main topic. Fish are a large part of the lifeforms that can hear the ships, therefore their hearing capabilities are discussed in Chapter 4. The procedure, algorithm for processing the data and the results of the vibration measurements that were performed on the ferry MF Glutra will be discussed in Chapter 5. Chapter 6 goes into the signal analysis performed for this thesis, this is the largest part of the thesis work, and will present several different procedures for characterising ship noise. Chapter 7 describes the main functionality of EcoNoise and describes the graphical user interface that was developed for EcoNoise as a part of this thesis. Chapter 8 consists of a discussion and conclusion of what has been presented in this report. There is also an Appendix attached, this describes the functions and subfunctions that were needed to implement the graphical user interface.

2. Underwater sound propagation

In this chapter the basics of underwater sound propagation will be discussed. The topics that follow are intended to provide the necessary insight required for calculating the sound level radiated from a given source to a receiver. The sound wave itself is a wave of moving particles bumping into each other, this is how the sound energy spreads. As the wave spreads, it will both experience geometrical spreading and absorption, leading to a decaying sound energy. The water column, the water between the sea surface and seabed, is regarded as a waveguide restricted by the surface and bottom. The sound is reflected at both restrictions composing a more complex sound field than what would be the case with free field.

2.1. Describing underwater sound propagation

2.1.1. Sound level

Sound is a consequence of the movement of particles. Without a surrounding medium, like in a vacuum, sound is not non-existent. The medium has a great influence on the propagation of sound, sound waves behave differently in air and in water. Underwater, when one water particle is displaced it bumps into another water particle and back again, the same process happens repeatedly, over large distances. This is a phenomenon known as a compressional wave. The sound pressure is defined as [5]:

$$p = v \cdot \rho \cdot c \tag{2.1}$$

where v is the particle velocity, ρ is the density of the medium and c is the speed of the compressional wave, the sound speed. What can be measured in this process is the pressure which the particles impose. The unit for pressure is Pascal, which makes it the natural unit also for sound pressure. Within acoustics, the range of pressure values that are considered is vast. Using the logarithmic decibel scale, the values used in calculations become a lot more comprehensible, and is defined using the decibel scale [6]:

$$SPL = 20\ log_{10} \frac{p}{p_{ref}} \tag{2.2}$$

where p is the pressure and p_{ref} is the reference value, which for underwater acoustic applications is 1 μPa.

2.1.2. Sound speed in water

The sound speed in water is affected by several factors, the temperature, pressure and salinity. This causes the sound speed to vary with depth, as well as location, however, the latter is normally ignored in calculations for simplicity. The varying sound speed causes the sound rays to be refracted as they propagate. They are bend in the direction of lowest sound speed, because the part of the wavefront which travels with higher speed will travel longer than the parts of lower speeds. The refraction is described by Snell's law [6]:

$$\frac{cos\theta_1}{cos\theta_2} = \frac{c_1}{c_2} \tag{2.3}$$

where θ_i are the grazing angles of the sound rays on each side of a transition of sound speed and c is the sound speed in the corresponding layer.

2.1.3. Source level

The sound level which is radiated from the relevant source is vital for calculations and simulations, and is also essential when trying to regulate emitted noise. It is normally described in relation to the sound level at a reference distance of one meter. This distance is helpful for the simplicity in calculations. The source level is defined in dB relative to a sound pressure of 1 μPa as [6]:

$$SL = 170,8 + 10\ log_{10}(W) + DI_s \tag{2.4}$$

where W is the radiated acoustic power by the source, while DI_s is the directivity index of the source.

2.1.4. Transmission loss

The transmission loss varies from location to location and case to case. It increases over distance, and is also dependent on the bathymetry, the sound speed as well as the reflections and transmissions at the seabed interface. Acoustics absorption also influence the total transmission loss, this is low for the lower frequencies but as the frequency increases the absorption gets more influence. The most significant part of the transmission loss is a result of geometrical spreading. Which is a result of the fact that the energy radiated is spread over a larger and larger area as it spreads. At short distances, where the depth is larger than the distance, the radiated sound spreads spherically because it spreads without obstacles the energy is spread over the area of a sphere. The spherical transmission loss is defined as [6]:

$$TL = 20\ log_{10}\left(\frac{r}{r_0}\right) + (r - r_0)\alpha_{dB} \tag{2.5}$$

r and r_0, are respectively the distance between the source and receiver and the reference distance, which is usually one meter. α_{dB} is the attenuation given here in $\frac{dB}{m}$. At large distances, where $r \gg r_0$ the expression can be shortened to [6]:

$$TL = 20\ log_{10}(r) + r\alpha_{dB} \tag{2.6}$$

When the distances are larger than the water depth, cylindrical spreading is used. It considers effect of the reflections at the seabed and surface. These reflections are contributing to the sound field. They will lead to positive and negative interference, but overall the reflections give a positive contribution. The cylindrical transmission loss is defined as [6]:

$$TL = 10\ log_{10}(r) + r\alpha_{dB} \tag{2.7}$$

In some cases, it is useful to use spherical spreading up to a certain distance, normally where the distance equals the depth, and onwards from there, use cylindrical spreading.

2.1.5. Lloyd mirror effect

When the sound is reflected by the water surface, an interface which is considered a smooth surface and reflection coefficient -1, which is caused by the vast difference between the two media. This negative reflection coefficient is what causes the second term in Equation (2.8) to be negative. When considering the roughness of the surface caused by waves, the surface will cause a not total reflection. The minus sign in the reflection coefficient means that the energy is reflected with a phase shift. The reflection interferes with the sound coming directly from the source, causing positive and negative interference in the nearfield, which is visible as minima and maxima at different ranges, this effect is known as the Lloyd Mirror Effect. At larger distances, in the far field, the transmission loss increases to 40 $log(r)$. The total field in the near field can be described by the formula [8]:

$$p(r,z) = \frac{e^{ikR_1}}{R_1} - \frac{e^{ikR_2}}{R_2} \tag{2.8}$$

where $k = \frac{2\pi}{\lambda}$ is the wavenumber, while R_1 and R_1 are respectively the direct range and the distance with a reflection from the water surface [8]:

$$R_1 = \sqrt{r^2 + (z_r - z_s)^2} \qquad R_2 = \sqrt{r^2 + (z_r + z_s)^2} \tag{2.9}$$

where r is the range from source to receiver without considering different depths, and the z_r and z_s are the depth of the receiver and source respectively. The number of minima is dependent of the depth of the source and the receiver as well as the frequency. Higher frequency gives a shorter wavelength, this implies that the distance between the minima is small, and therefore gives more minima than a lower frequency.

2.1.6. Doppler effect

The measurements that were performed are measuring a moving source. This implies that the Doppler effect will influence the results. It is therefore important that its effect on the results is known. The Doppler effect causes a change in the frequency between the source and receiver when either or both are moving. The Doppler effect is also dependant of the angle between the direction of movement of the moving object. However, here the maximum possible Doppler effect is of interest, this occurs when the angle between source and receiver is 0°. In this case the perceived frequency at the stationary receiver is [6]:

$$f_r = f_0 \left(\frac{v_t \ + \ c}{c} \right) \tag{2.10}$$

where f_r is the perceived frequency at the receiver, f_0 is the frequency transmitted by the source, v_t is the speed of the source and c is the sound speed. The maximum speed recorded in the measurements that were made available was 12.5 *knots* or 6.43 m/s. This corresponds to a frequency change of maximum 0.43 %. The frequency shift leards to that some of the energy in each frequency band will be shifted to another band. This means that some energy will have a frequency shift. The effect is mostly relevant for the applications which are described in Section 6.3, and is important to keep in mind. For the speed considered, a 1/24-octave band between the frequencies of $100.14 - 103.07$ Hz will be shifted to $100.57 - 103.51$ Hz. Which is not an excessive frequency shift. However, for this case the effects are not too big. But if measurements that include vessels with higher operative speeds this must be considered when running this algorithm.

2.1.7. Ray tracing as a tool for simulation of underwater sound propagation

Ray tracing is a way of simulating underwater sound propagation. By sending many rays from a source, these rays will be reflected from the water surface and bottom and refracted as discussed in Section 2.1.2. Through receivers that counts the number of rays they have received, the sound field can be synthesized. Bellhop [19] is a ray tracing program which will be used later in this thesis. For deeper insight, the manual and user's guide is suggested reading [19].

2.2. Vibrations

The ship hull is composed of plates. These plates may vibrate when they are subject to external vibrational stimulus. Finite structures, when allowed to vibrate freely will vibrate in one or more of their resonance frequencies. These natural frequencies also play an important role in the resulting vibrations when the structure is subject to external excitation. The response can be calculated as a sum of the natural frequencies [20]. The closer the excitation is to one of the natural frequencies, the stronger the response will be. The vibration of plates in water will radiate acoustic energy out into the water, and this is of great interest when studying ship noise.

Research in the 1960s showed that clamped plates radiate most efficiently, while freely supported plates radiate approximately half the energy and the radiation of free plates is regarded to be very small [20]. The transverse displacement of a plate may be described by the differential equation [11]:

$$D\nabla^4 w + \rho \frac{\partial^2 w}{\partial t^2} \tag{2.11}$$

where D is flexural rigidity, and is given by:

$$D = \frac{Eh^3}{12(1-\nu^2)} \tag{2.12}$$

where E is Young's modulus, h is plate thickness, ν is Poisson's ratio, ρ is the mass density of the material and ∇ is the Laplacian operator.

In plates of different materials, the sound speed will differ. The longitudal wave speed in plates, c_p, is given as [20]:

$$c_p = c_l \sqrt{\frac{1}{1-\nu^2}} \tag{2.13}$$

where c_l is the compressional longitudinal wave speed in a thin rod, which is defined in Equation (2.14) and ν is the material's Poisson's ratio. The compressional longitudinal wave speed in a thin rod is given by [20]:

$$c_l = \sqrt{\frac{E}{\rho}} \tag{2.14}$$

where the parameters are as described above.

The phase speed of the bending wave is as for a thin rod dependent of the frequency [15], which implies dispersion. Dispersion is the effect that the different frequency contents of the signals travel at different speeds, reaching the observer at different times, and therefore cause distortion to the signal [15].

When assuming that the boundaries are simply supported, the displacement at the edges should be equal to zero, and the vibrational modes are given by [24]:

$$V_y(x,z) = A_y \sin\left(m\pi \frac{x}{a}\right) \sin\left(n\pi \frac{z}{b}\right), n, m = 1, 2, 3.. \tag{2.15}$$

where A_y is the amplitude, and a and b are the sides of the plate. If the boundaries are not simply supported as is required in Equation (2.15), mode functions for other assemblies can be found in [11]. All of these equations differ from the corresponding equations for modes of airborne sound in rooms in that there is no $(1,0)$-mode or vice versa. Both indices must be at least one. This is due to clamping at the sides, making the displacement at all edges equal to zero. Through solving this equation, it is possible to derive the expression for the eigenfrequencies of a homogeneous plate [24]:

$$f_{n,m} = \frac{\pi}{4\sqrt{3}}\, c_l\ h \left[\left(\frac{n}{a}\right)^2 + \left(\frac{m}{b}\right)^2\right],\ n, m = 1, 2, 3.. \tag{2.16}$$

where h is the thickness of the plate and c_l is the longitudinal sound speed of the medium. The sound speed is the only parameter describing the medium when calculating the eigenfrequencies. All complex vibrational pattern may be described by a sum of the modes.

The number of vibrational modes in a plate is in contrast to that of the thin rod not frequency dependent. The number of modes in a given frequency band with an arbitrary centre frequency is given by [15, p.145]:

$$\Delta N = \frac{1}{2} S \sqrt{\frac{m'}{D}} \Delta f \tag{2.17}$$

where $m' = \rho * h$, in other words the density of the material times the thickness, the weight of the material can be found by multiplying m' with the area.

2.3. Vibrational simulations

To assess the frequencies that can be expected for a ship with plates of given dimensions, Equation (2.16) was used. This was the alternative to performing the actual measurements onboard the fishing vessel which was the original plan. This can enable the possibility to predict the frequency intervals where it is likely that the vibrational modes are located for a given plate.

2.3.1. Effects of the ship hull plate dimensions

As stated in Section 2.2 the most important factors for the location of the vibrational modes in the frequency domain are:

- Width
- Height
- Thickness
- Material

These parameters play an important role in the frequency domain. If it is desirable to change the vibrational characteristics of a given plate, the simplest procedure to accomplish this will be to change the area of the plate. A result of Equation (2.16) is that a smaller area gives fewer modes with low frequency. Example values where used to predict the possible frequencies where which modes can be located for a typical plate.

The modes in two different plates are shown in Figure 2.1. Their parameters are stated in Table 2.1. As the thickness increases the frequency of the given modes are also increasing. The difference between the frequencies of the different modes are also increasing when the thickness is larger.

Table 2.1.: Parameters of the plates which modes are shown in Figure 2.1.

Width	Length	Sound speed
1 m	4 m	5000 m/s

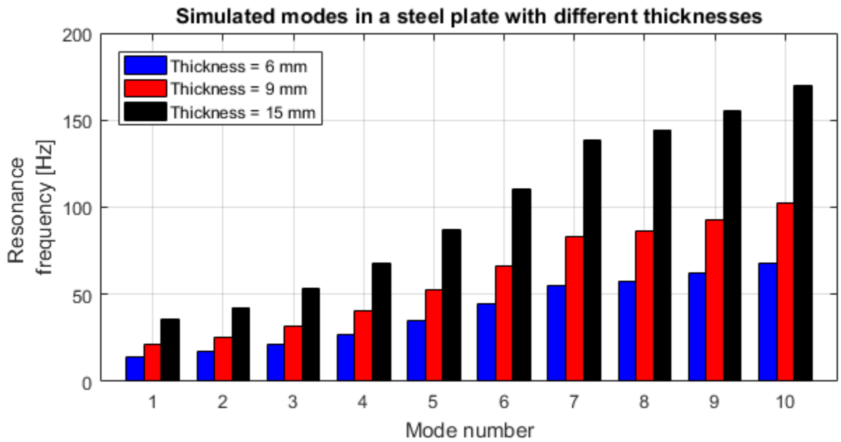

Figure 2.1.: Different modes and their corresponding frequencies with different thicknesses.

The thickness of the ship hull plates is not easy to change after the ship is build. But this parameter can be included in the design process of the ship by trying to avoid an excessive amount of modes in the region where the vibration stimulation from the propeller and main engine is strong. This can potentially decrease the radiated sound level of the ship.

From Figure 2.1 and 2.2 it is evident that all the combinations have several modes at frequencies in the audible frequency range of both cod and haddock, as well as many other species. The important difference between the plates that are presented is the modal density, some plates have fewer modes in the audible range, and this is an advantage because they are likely to emit less noise in this frequency range. However, this might lead to sound radiation in other frequency bands, but from the fishing vessel's point of view, this is not vital.

When the ship is build and is operative, it will be easier to alter the boundary conditions of the plates. They are normally held in place by ribs, acting as the frame or the skeleton of the ship. The alteration of the dimensions can for example be done by welding bars in between ribs of the hull. By doing this the hull and plates would be stiffened and the natural vibration pattern would be altered. It is plausible that these changes to the ship hull will change the boundary conditions of the plates. By shortening the width or length of the plates, some of the otherwise natural mode behaviour would be altered, and thereby changing the pattern of modes.

Figure 2.3 shows the mode shapes of some of the lowest modes. These plots give an idea of how the above-mentioned preventive measures can be implemented. By stiffening the plate at locations that are particularly exposed to excessive vibrations at the resonance frequencies, the vibrational characteristics of the plate will be altered. The dimensions of the plates will then be smaller, something that in turn will increase most of the resonance frequencies of the new plate dimensions.

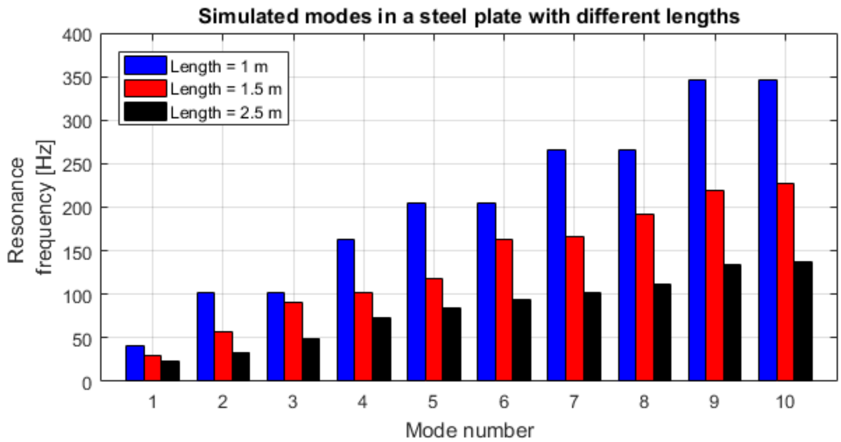

Figure 2.2.: Different modes and their corresponding resonance frequencies with different plate lengths, the width and sound speed are the same as in Table 2.1, however the length of the plates is varying and the thickness is now fixed at 9 mm.

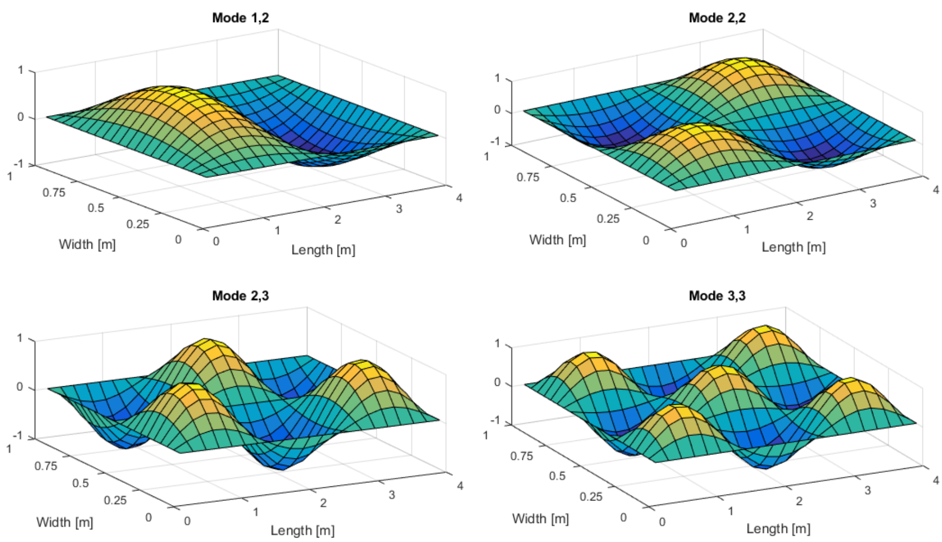

Figure 2.3.: Different mode shapes, the dimensions of the plate in this case is 4×1 m.

3. Ship noise

Every sound is generated by a source. As discussed in Section 1.1 the increasing sound level in the oceans is a growing problem, and is influencing (and is likely to cause harm) to marine life. Most of the literature focuses on the dominant noise sources of the seas; ship noise, seismic airguns and pile driving. But here the focus is on noise generated by ships.

The noise radiates from a ship is hard to estimate from the data describing the ship. The different classes of ships have different usecases, and this plays a role. The current operations condition change the properties of the ship, the weather also plays a role in the measurements and the ship performance. However, it is important to have a basecase example of how the ship radiates noise. Although the noise is hard to estimate, every ship emits noise in certain frequency bands specific to itself. It can be compared to a fingerprint from which it can be identified by, this will be discussed further in Section 6.4. This is important in naval operations, but the applications can be broadened. In the next sections the relationship between the vessel and the noise it radiates will be discussed.

3.1. Engine noise

As reported in [1], the engines that are normally the largest contributors are the main engine and the service generator. It was also found for lower speeds that the service generator is the dominant noise source. But when the speed increases, the main engine becomes more and more dominant. This increases the strain the main engine is subject to. As will be discussed in Section 3.2, the propeller is rotating at the same speed, but it takes more power to rotate it when the pitch of the propeller is changed to increase the speed.

A simple explanation of why engines are emitting noise is that engines are composed of many moving parts, this will inevitably emit sound as Ross stated in the quote in Section 1. These parts are moving constantly, and interacting with each other, these interactions happen at specific intervals. The frequency radiated from each noise component is a consequence of the duration of these intervals.

Table 3.1.: Main vibrational frequencies in a diesel engine.

Cause of vibration	Frequency of vibration
Cylinder firing rate	$f_{cfr} = \frac{k \cdot rpm}{2 \cdot 60}$
Crank shaft	$f_c = \frac{k \cdot rpm}{60}$
Engine valves	$f_v = \frac{k \cdot z_p \cdot n_s \cdot z_z}{m \cdot 60}$
Piston slap	$f_{ps} = \frac{k \cdot z_p \cdot n_s}{60}$
Piston rings	$f_{pr} = \frac{k \cdot b \cdot z_p n_s}{60}$

where the variables are as follows:

- k - integer representing the number of the harmonic
- rpm - the number of the engines rotations per minute
- z_p - the number of pistons in the engine
- z_z - the number of valves for one piston
- b - the number of piston rings for one piston

As listed in Table 3.1 there are many sources of noise in the engine. Because they are in a large degree dependent of the same parameters, they are overlapping several times. This is because the other actions, for example the piston slap is happening several times during a crank shaft revolution, the piston slaps are not equally spaced, so the fundamental frequency is the same as for the revolution of the crank shaft [20]. A piston slap is the impact of a piston into a cylinder wall, which takes place after the piston has been riding against a cylinder surface and it moves to the other side with great energy and hits the cylinder wall, which generates strong vibrations.

When the engine has more cylinders, the angular connections between the crank shaft need to be staggered to deal with dynamic unbalances. This causes the piston slaps that occur at the same time as a revolution of the crank shaft to have more influence than the other piston slaps. The rate at which this occurs is known as the firing rate [20]. This is overlapping the crank shaft revolution, which yields the most prominent level of the frequencies.

Figure 3.1 shows the frequency content of the measurements in [1]. The band width used was $0,5\ Hz$, and the sources of the sound corresponding to peak frequencies are indicated in the figure. The ship in question is here a modern cargo ship, which is significantly larger than the fishing vessels that are otherwise discussed in this thesis, and direct comparisons between the noise levels can be misleading. The bands with the sound stemming from the engine are indicated here as well as from the propeller which will be discussed in the next section.

3.2. Propeller noise

The propeller is together with the machinery a ship's main noise sources. Arvesson and Vendetti [1] summarized the reasons for the radiation from the propeller with

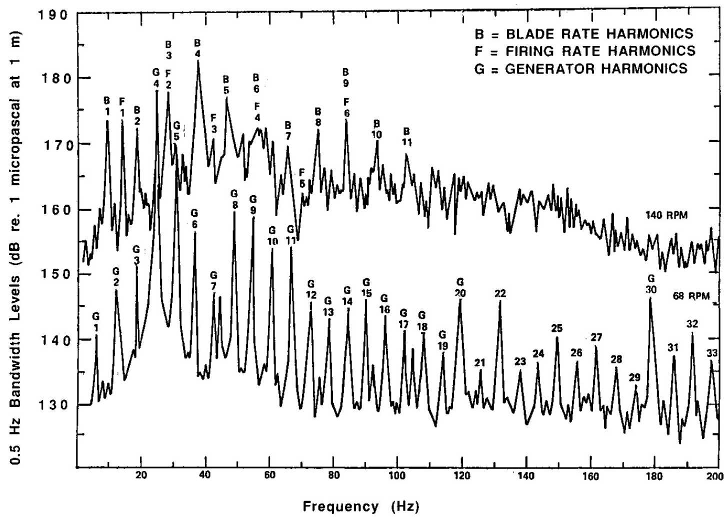

Figure 3.1.: Frequency levels of the ship measured by Arveson and Vendetti. Figure from [1].

that the propeller is operating behind a hull which creates a variable inflow velocity. The differences in velocity causes the pressure on the propeller blades to vary and is also dependent of the depth at which it is located, as the pressure increases with depth. This causes the pressure to be at its lowest at the upper part of the propeller. If the propeller is rotating fast enough, this causes a cavity to be formed. However, as the blade is rotating the cavity is also rotating, and as it goes down again, to the lower part of the propeller, the pressure increases again and causes the bubble to collapse. This causes tonals with a frequency related to the number of blades on the propeller and the number of rotations it does and is given by [25]:

$$BR = \frac{n_b \cdot rpm}{60} \tag{3.1}$$

where n_b is the number of blades on the propeller and the rpm is rotations per minute of the propeller. There has been a trend for many years toward direct drive propulsion with adjustable pitch propellers. This increases the efficiency, and means that the propeller is directly coupled to the main engine. Such a system implies that the propeller is only operating with one specific rpm, and causes the blade rate of the ship to be fixed.

3.2.1. Cavitation

The noise originating at the propeller discussed in the section above can also be considered as cavitation. But cavitation is also the source of a broadband emitted noise, witch is a result from a chaotic process of bubbles being generated and bursting.

When the cavitation process has become more developed, the high frequency content has been observed to decrease in strength [20]. A reason for this can be the decrease in sound speed in waters with a high amount of bubbles. Another possibility is that the gas content in the cavitation bubbles increases, and hence dampens the collapse of the bubble and therefore reduces the sound radiation. Cavitation is one of the main contributors to the radiated noise from ships, with great influence from 5 kHz to over 100 kHz [20].

3.3. Ship hull vibrations

When the ship is radiating noise with a frequency for example corresponding to the *rpm* of the main engine, the noise is not directly going from the engine to the sea. The noise the engine makes is related to the vibration. The engine is rigidly mounted to the hull. Giving the vibration a path to travel to the outer hull, where the ship hull plates are vibrating as a result of the vibrations in the engine. Ross [20] argues for dividing the noise production process into three parts:

- Generation of a vibratory motion
- Transmission of the vibration to a radiating surface
- Radiation of the sound into a surrounding medium

These three factors can be combated by for example isolating the radiating surfaces from the vibrations or reducing the radiation efficiency of the surface [20].

However, the vibration in the plates of the hull can be excited by more than vibration in machinery. Another source is known as flow noise, which is excited by turbulence. It is especially important when the fluid is interacting with a boundary [22].

The ship hull is a large and complex structure. Due to the complexity, calculating the vibration and radiation from such a structure is regarded to be virtually impossible. However, it is possible to simplify it and get reasonable results. Vibrations in plates is the basis for considering the vibrations in the ship hull and was discussed in Section 2.2.

Donald Ross [20] divides the noise radiated from the hull into three intervals, high, medium and low frequency. The listed frequencies or wavelengths indicate the start and beginning of a frequency interval in which there are numbered hallmarks that are typical for the frequency range, the list is recreated from a table in [20, p.100].

- $f > 20\ kHz$
  1. Small section vibrates, extending only a few frames
  2. Ribbed flat plate
  3. Curvature adds stiffness at low-frequency end
- $\lambda \approx R$

1. Compartments vibrate
2. Resonances important
3. Cylindrical shell in a rigid cylindrical baffle

- $\lambda \approx \frac{L}{2}$
  1. Whole body involved
  2. Rigid-body translation and rotation
  3. Beam flexural vibrations (whipping)
  4. Accordion modes
- $f \approx 1\ Hz$

where L is the length of the ship and R is the effective cross-sectional radius. The frequencies of the lowest frequency interval are mostly cancelled by a mirror source within the length of the hull sources [20]. While the higher are relevant for acoustic calculations and observations. The frequencies in the highest range can be calculated through plate theory. What is important to consider when dimensioning the ship and its structure is the rotational speeds of the main contributors to the radiated noise. If the corresponding frequencies are overlapping with vibrational modes, this can cause excessive vibration with that frequency.

4. Fish hearing

Ship noise impacts marine life. If the fish could not hear the fishing vessels, it would not be as important, more as a tool for diagnosing the ship conditions. The fact that fish can hear is not something people take for granted. It is normally only considering when one is out fishing. Then it is important to have the boat to be as quiet as possible not to scare the fish away. This is the case for larger fishing vessels as well, only this is a larger task. The first account of fish that includes the fact they can hear originates from the first century CE [18]. But it was first shown through the work of among others, Parker and von Frisch that fish detect sound with the ear [18]. It has been normal to divide fish species into different groups corresponding to their hearing abilities, this will be further discussed in the next section.

4.1. Sensing particle motion and sound pressure

The hearing functionality of most fishes are based on sensing particle motion. The functionality is best described by Popper and Fay [18]: "*In the simplest explanation, the fish body and sensory epithelia, which are of approximately the same density as water, move with approximately the same amplitude and phase as the motion of water particles in a sound field, with the primary response being to the particle motion component of the sound field, whether in the near or far field. The otolith or otoconial mass, which is about three times denser than the rest of the body, is also set into motion but with a different amplitude and phase than the rest of the body. Since the ciliary bundles are "connected to" the otolith either through direct contact or through the otolith membrane.*"

Most of the different hearing functions are based on the use of the swim bladder, a gas bubble used mainly to maintain the position in the water column. The degree of which it contributes is dependent on the distance from the swim bladder to the ear. It functions by the change in volume of the swim bladder because of the varying pressure given by the sound pressure wave of the sound field. The vibratory motion of the bubble radiates the same signal out again, as a signal of particle motion, which is transferred via a physical connection to the otolith organ.

4.2. Hearing capabilities

Acoustic communication between fish is important. It is vital among other things for the spawning process. It is used by many species to attract other fish for reproduction. The potential effect of anthropogenic noise is masking, that the

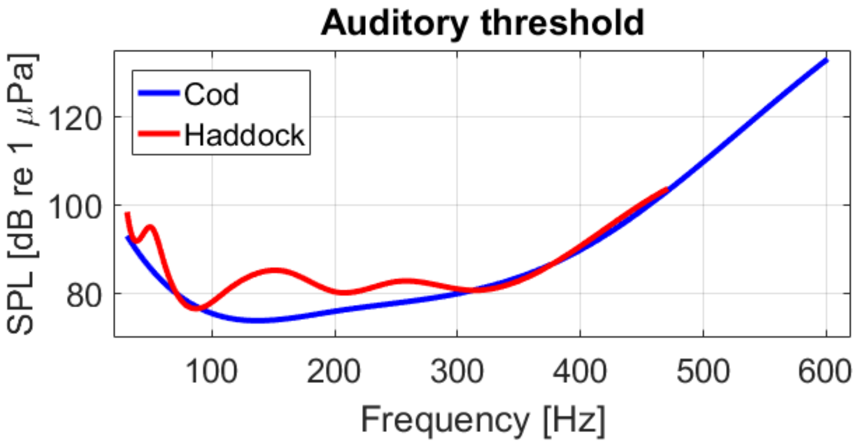

Figure 4.1.: The hearing threshold for cod and haddock which were used as reference in calculations.

communication signals between the fish become inaudible due to the higher intensity of the anthropogenic noise in the same frequency range. In [10] it was found that spawning cod made a significant contribution to the overall noise level under 500 Hz in the spawning season. These frequencies are coinciding with the large part of the energy in the anthropogenic noise sources, making the communication signals susceptible for masking. There is a clear overlap between the frequencies used for communication between fishes and the noise emitted from ships. This can indicate that the ship noise can mask the signals. This can be disturbing and in the worst case harmful to for example the spawning processes, which will lead to diminishing fish populations.

Figure 4.1 shows the auditory thresholds of cod and haddock. The values for haddock were found in [16] and for cod in [7]. It is clear from the figure that cod has better hearing capabilities than haddock. The effects the difference in hearing capabilities can have is shown in Section 6.3.3 range at which the frequencies from the vessels become audible. The thresholds are interpolated from sound level thresholds at certain frequencies. The interpolation was done in Matlab using splines. The hearing thresholds can be useful when assessing the impact different sounds can have on the fish.

4.3. Behavioral response

It is challenging to find a definite answer for the effect anthropogenic noise sources might have on fish. In [3] fish were subject to noise and their responses were recorded, the most typical reactions to the noise were:

- Burst swimming

- Swimming in tighter groups
- Swimming towards the bottom of the cage, which had a lower sound level
- Flash expansion

It was also found that the fish had less alarm responses to the subsequent noise exposures in comparison to the first. However, it must be kept in mind that these experiments have been done on fish in captivity, this might have an effect on the results. The behaviour might be different if the fish would have been able to swim freely. It must be kept in mind that the behavior of the fish might differ in between the species, and it might differ within a species depending on whether the fish are wild caught or bred. If the fish is wild caught and transferred to a cage, there might be vast differences between the procedure of acclimation processes between studies, which can yield very different results [3]. Therefore the optimal solution would be to do these tests in the wild, in the native environment of the fish.

This effect has been mostly reported for marine mammals, and not too much in fishes. In [23] it was found that for several different species of fish, there was a linear threshold shift related to the sound pressure level the fish were subject to and a threshold shift that the fish experienced in the aftermath of the experiment.

As in human hearing, the duration of sound exposure has an effect. With longer duration of the exposure, the TTS (temporary threshold shift) might be higher than a shorter exposure of the same sound level [17]. The time where the hearing abilities of the fish are impaired, the fish is under increased danger because it is not able to detect dangers imposed by hunting rivals. Another approach to unveil the effects of the noise is to sacrifice the fish and dissect it to look at the damage that has been done to the hair cells in the inner ear [12]. The caveat to these two approaches is that the fish must be kept in captivity, making it hard to assess the natural behavioral responses the fish would have had if it was in the wild.

5. Measurements

The vibration of the ship hull can be assessed by performing measurements directly on the hull. The measurements were performed with an accelerometer. The accelerometer was connected to a charge amplifier. The sensitivity of the accelerometer can be compensated directly at the charge amplifier. The charge amplifier has several options, and the most important one is amplification, which indicates the size of the voltage regarding the acceleration the accelerometer experiences.

Table 5.1.: Measuring equipment

Type of equipment	Type name
Accelerometer	Brüel & Kjær 4370
Charge amplifier	Brüel & Kjær 2626
Recorder	Sound Devices 722

5.1. Measurement procedure and processing algorithm

The recorder was as stated in Table 5.1 a Sound Devices 722. It saves the input to a wave-file with values between 1 and −1. This in addition to other considerations must be accounted for when converting from the wave-file format to an acceleration time series.

The sensitivity of the accelerometer is accounted for directly in the charge amplifier by turning a knob on the front of the amplifier. Depending on the vibration strength the amplification of in the charge amplifier needs to be adjusted. The unit for the output is V/g, making the recording process more comprehensible. The recorder has a maximum value, for which it will denote in the wave-file as 1. The maximum value is normally given in dBu, which is corresponding to an actual physical voltage. The maximum value is also known as dBFS (dB relative to full scale). By comparing these two values, and taking the amplification that takes place in the recorder, the actual measured strength of the vibration may be assessed.

From the steps described above the vibration can be found as acceleration in g-units. To convert to m/s^2, the calculated values must be multiplied by the gravitational constant, 9.81. The relationship between acceleration, a, and velocity, v, is:

$$v = \int a \, dt \tag{5.1}$$

Figure 5.1.: Picture of the ferry MF Glutra, photo by Kim Roger Asphaug.

This means that the acceleration needs to be integrated to find the velocity. Integration acts as a lowpass filter. This implies that compared to the acceleration the velocity components of low frequency are relatively stronger than the components with higher frequency compared to the acceleration. With frequency components under 1 Hz, it is apparent that the amplification of the lowest frequencies because of the integration is excessive. To compensate for this effect, the velocity is high pass filtered, with a passband over 1 Hz. This affects the ability to study the vibrational components in the velocity domain under 1 Hz, where from Figure 5.2 it is clear that there is a contribution.

5.2. Vibration measurements on the hull of MF Glutra

MF Glutra, shown in Figure 5.1, is a gas-electric ferry operating between Flakk and Rørvik as part of the Norwegian County Road 715. It is known to be the world's first ferry run by natural gas. It has four LNG-engines, these engines are unlike the conventional ship placed over the ferry's car deck. The data describing the machinery of the ship can be found in Table 5.2.

Table 5.2.: Engine data of MF Glutra

Fuel	Engine type	RPM	Cylinders
LNG	Mitsubishi GS12R-PTK	1500	12 V

The placement of the machinery might have a significant impact on the radiated noise from the ship. The machinery induced vibrations might be attenuated on its way to the part of the hull which is in contact with water. The dimensions of the ship are found in Table 5.3.

Table 5.3.: Dimensions of MF Glutra

Length overall	Length of hull	Width
121.2 m	107.3 m	15.7 m

The measurements were conducted the 17. February 2017. There were only performed a few measurements on a relatively small area of the hull. The reason was that it the measurements were done as preparation for the measurements to be done on of Havfisk's fishing vessels, to familiarise with the measurement equipment. The sea conditions were calm, making the conduction of the measurements relatively easy. This also meant that the machinery was running smoothly and stable. The plan was to conduct the measurements in the engine room. However, as the main machinery is placed above the water line it would be more suitable performing the measurements in the lower deck. They were therefore performed below the main deck, in a technical room with direct access to service generators as well as the outer ship hull. Both vibration measurements of the ship hull as well as sound measurements were performed.

5.2.1. Vibration measurements

The vibration measurements were only performed on one location. For a more in depth series of measurements, it would be ideal to measure at different locations along the ship, and at different heights of the hull. With more measurements, it would have been possible to gain more insight into the vibrational patterns and modes of the ship. Also, how the vibrations are propagating through the structures of the ship.

Vibration can be described in more units, such as in Figure 5.2. Here it is given as acceleration and velocity. Acceleration because that is a direct derivative from the recorded values, and velocity because the velocity can make it easier to find a connection between the vibration and the radiated noise. The theory says that the sound pressure can be deduced from the particle velocity together with the impedance of the matter as in Equation (2.1). As stated in Section 5.1, intrinsic in the integration process there is lowpass filtering taking place. The lower the frequency of the acceleration componenent, the larger the contribution from the same component will be to the velocity spectrum.

The most prominent peak of both spectra is located at 50 Hz. This is the second harmonic of the engine rpm. When studying the peak of the first harmonic of the engine rpm, at 25 Hz, the lowpass effect is clear. Relative to the other peaks, this has gained significant strength.

5.2.2. Microphone recording

In addition to the vibration measurements, a microphone recording was also performed. The microphone used was the internal microphone in a mobile phone

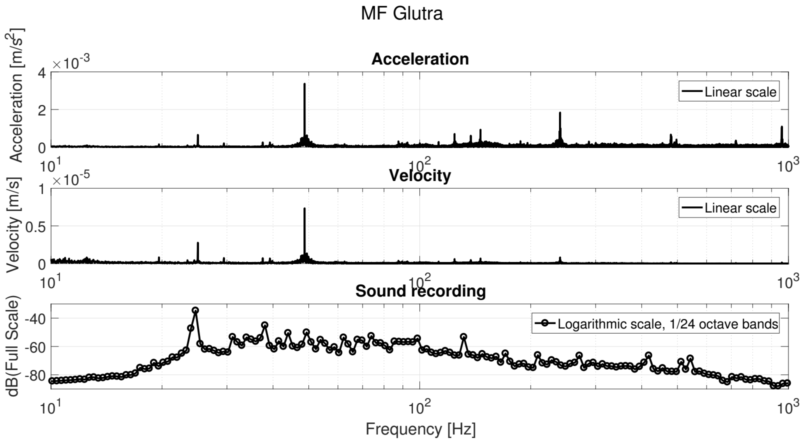

Figure 5.2.: Frequency spectra of sound and vibration measurements from the lower deck of MF Glutra.

(Motorola Moto G4), using the app Audio Recorder. The recording was done while measuring the hull vibration. The length of the recording was about four minutes, while processing the signal it was made sure that the time window used did not include any disturbances from irrelevant sources. Such as for example interactions between ferry and pier or talking. The sample rate of the recording was $f_s = 44.1\ kHz$. The minimum time window was set to be 30 s, making the time window approximately 47 s due to the accordingly optimal length of FFT.

The most prominent peak is located at 25 Hz which corresponds to the first harmonic of the engines' rpm. The higher harmonics of the engine frequency are present, however not particularly prominent compared to the vibrational spectra.

6. Signal analysis

For the main part of this thesis, measurements of four of some of Havfisk's fishing vessels were made available for analysis. In this thesis, the focus has been on the measurements of the fishing vessels Kongsfjord and Vesttind. The measurements were carried out by Ecoxy AS in 2015.

With the use of these data sets, several different ways to analyze the noise generated by vessel will be discussed. The different approaches that will be looked at are:

- Octave band filtering: Section 6.2
- Tracking frequencies over distances: Section 6.3
- Distance defined frequency signature: Section 6.4
- Directionality analysis: Section 6.5

The algorithms have been customized and improved through the work in this thesis. Some functionality has been added. The next section describes the measurement procedure, while the rest of this chapter describes the algorithms and the results.

6.1. Description of the measurement procedure

At the time of measuring, a hydrophone was placed at the seafloor and connected to a buoy at the surface. The vessels to be measured sailed back and forth past the hydrophone several times. After passing the hydrophone the vessels continued in the same direction for some time before turning 180° to come back in the opposite direction. Each single measurement, sailing past the hydrophone once is referred to as a *run*.

Figure 6.1 shows how the vessels sail past the hydrophone. The CPA (closest point of approach) is indicated as a circle on the vessel's path. This is the point where the distance from the vessel to the hydrophone is at its minimum. It was for each run defined as the point where the sound level is at its maximum. The T_1 and T_2 indicate the cut off times for the analysis. Only the measured values in the time interval between these two points in time are analysed. By measuring the vessel several times, it was a possibility to sail with the vessel under different conditions. It was experimented with running different combinations of equipment and engines in some of the different runs. Most of the runs are without the trawl, but the runs with significantly lower speeds around $4-5$ *knots* are runs with the trawl in the water.

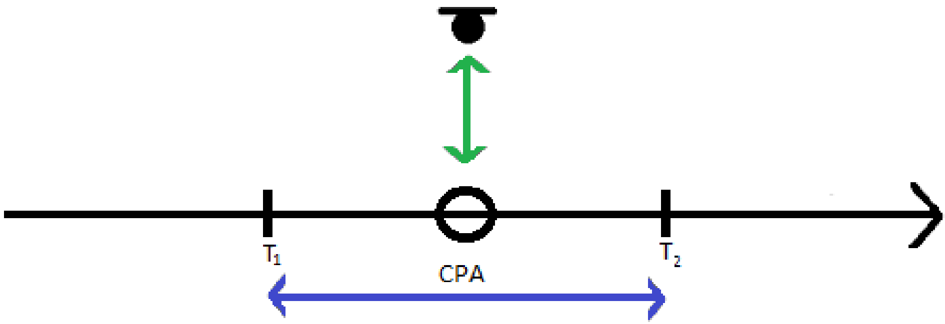

Figure 6.1.: The path of the vessels sailing past the hydrophone.

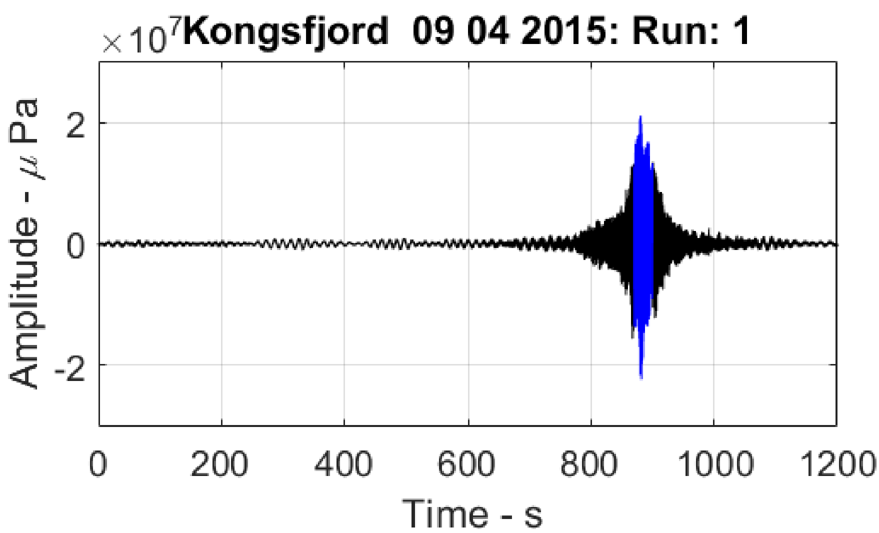

Figure 6.2.: Time series of the measurement of Kongsfjord, run 1.

Figure 6.2 shows the time series of the measurement of the first run of Kongsfjord. The blue part indicates the part of the measurement that is used to the spectrum that is used when calculating the frequency spectrum, while the black part indicates the rest of the signal which is not used when calculating the spectrum of the radiated noise. This is according to the *Silent class*-rules which requires at least 30 s of measurement to be used for analysis. The selection is done by centring the time segment around the CPA and choosing a cut off at approximately 15 s on each side, in Figure 6.1 the cut offs are indicated as T_1 and T_2, and the time segment that will be analysed as the blue arrow.

6.2. Octave band filtering

The main function of the EcoNoise-package is the frequency analysis of the signal and octave band filtering the signal in frequency domain. An octave is the interval between two frequencies where one frequency is twice as high as the other frequency. This means that an octave band is the band between a lower limit frequency, f_l and an upper limit frequency, f_u, where the frequencies are defined as [15]:

$$2 \cdot f_l = f_u \tag{6.1}$$

This band will include all frequencies between the lower and upper limit. The band filters can have variable widths. The width of the octave band filters that have been used here are 1/3 and 1/24. With a 1/3-octave band, the frequencies are assigned to three bands for each the octave, while a 1/24-octave-band filter has 24 bands for each octave. The relationship between the centre frequency and the upper and lower frequency limits are defined as [15]:

$$f_{centre} = \sqrt{f_l \cdot f_u} \tag{6.2}$$

where f_{centre} is the centre frequency of the filter, and f_l is the lower limit of the pass band and f_u is the upper limit. The relationship between the lower and upper limits is given in the equation below [15]:

$$f_l = \sqrt[Q]{2} \cdot f_u \tag{6.3}$$

where f_l and f_u are as described above and Q is the width of the octave band. The signals were first filtered with a 1/3-octave band filter because this is the standard according to the *Silent Class*-rules [2].

$$SL(f_{centre}) = \frac{1}{n_{stop} - n_{start} + 1} \sum_{i=n_{start}}^{n_{stop}} S_i \tag{6.4}$$

where n_{start} and n_{stop} are integers corresponding to the upper and lower frequency limits, f_l and f_u and S_i is the power spectrum in the ith frequency band. In this way, the sound in each band is assigned to the centre frequency index in the variable SL.

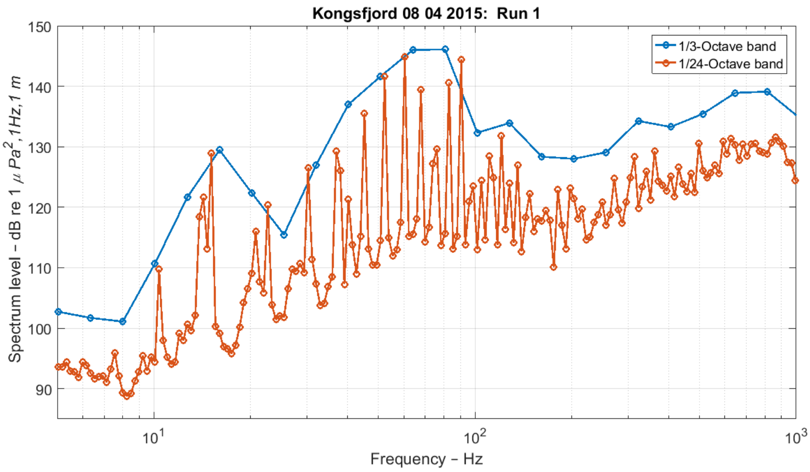

Figure 6.3.: Kongsfjord run 1, filtered with 1/3 and 1/24-octave band filters.

However, when the results are filtered with the 1/3-octave band, the resolution is not high enough to distinguish the harmonic frequencies stemming from the propeller or main engine. These frequencies show themselves as peaks in the spectrum with higher sound levels than the surrounding noise floor. This means that the sound radiation might exceed the permitted levels when it is filtered with the 1/24-octave band filter, while when filtering with the 1/3-octave band filter it is under the permitted levels. The width of 1/24-octave was found to yield reasonable results as well as a higher resolution. The most important advantage is the increased resolution which makes identifying the harmonics resulting from the propeller blade rate and the firing rate of the main engine as discussed in Section 3.

In Figure 6.3 the resolution in the 1/3-octave band filtered measurement is too low to separate the peaks at the harmonics of the frequencies of the propeller and main engine.

6.3. LongRun

LongRun is a program designed to compute the sound levels of the vessel from different distances. This gives insight to among other things, the propagation effects. It divides the signal into shorter segments, by a length that may be changed. These smaller segments are Fourier analysed one after each other. This yields an array of sound levels measured at different distances. By doing this, the received level for each frequency band is tracked over distance from over a thousand meters before passing the hydrophone to approximately the same distance after passing the hydrophone. In this way, different characteristics of the ship can be observed on different distances.

This feature can be very useful when assessing ship noise from fishing vessels, because it is possible to see where and when the sound level received at a specific distance is audible for different fish species. This can be done by weighting the different octave bands with the corresponding hearing capabilities of the relevant fish species. In this way, the sound level is now referenced to the hearing capabilities of the fish. Another way of achieving this is to plot the level of a single band together with the corresponding auditory threshold of the fish as a line. When the level of the signal dips below the line indicating the threshold, it is in theory inaudible to the fish.

This metric can prove itself to be very useful. It is easier to grasp and use and might make more sense for users without a working knowledge in underwater acoustics. The ability to concentrate the whole question of how much noise the vessel is radiating to how far away a fish can hear it can be a useful simplification. The amount of knowledge that is established about how the fish hears is also an argument for simplification. The hearing capabilities of fish is normally assessed through two thresholds, the hearing threshold, and the startle threshold. Respectively at which sound level the sound becomes audible and when the fish startles when the fish is subject to the sound. There is not much known about what difference a few decibels do to the impact the noise has on the fish. So instead of focusing on how much the vessels radiate in frequency bands outside the hearing capabilities, it would be an idea to focus on which distance to the fish the vessel becomes audible.

The metric would be better suited for fishing vessels for tests of this kind than for other kinds of ships, where the focus is more environmental. There are a vast number of different species of fish and mammals and more in the oceans, with very different hearing capabilities, so it is suited for a use case where the concern is only the effects of the noise on a single species, or species close to each other with similar hearing capabilities.

6.3.1. Drawbacks of the method

When studying the results with the weighted distance plots, in some cases it can be challenging to distinguish the different runs. This happens at larger distances where the sound level is starting to increase. Another issue is verifying that the noise source actually is the vessel under investigation. Possible reasons for this can be that the segmentation of the main file into the shorter files for each run was imperfect or that the vessel sailed a too short distance away from the hydrophone before turning around, which can cause *interrun interference.* These artefacts show themselves as audible components at distances of $4500 - 5000\ m$, which is unlikely, and can be discarded after comparing with the measurement in time domain which show irregularity.

6.3.2. Studying transmission loss

As this algorithm tracks the sound level received at different distances it gives a good estimation of the transmission loss that is occurring. The sound level of the

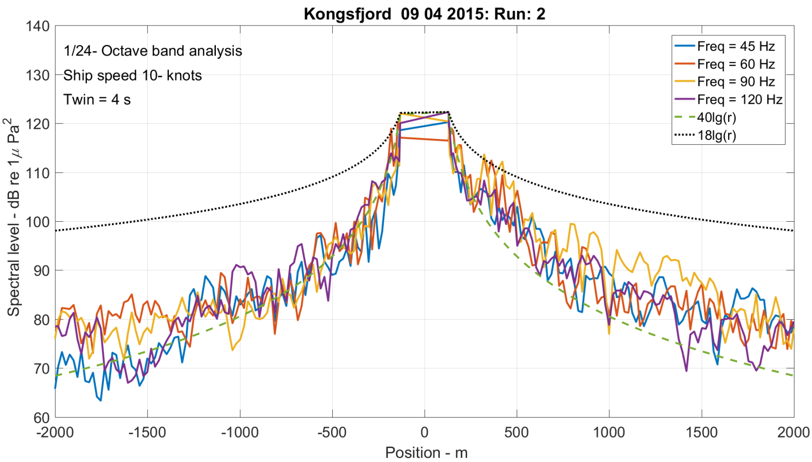

Figure 6.4.: The sound level of the four most prominent frequency bands of Kongsfjord, plotted together with two dotted lines, the shortest of the dotted lines is 18 $log(r)$ and the longer is 40 $log(r)$.

different frequency bands can be plotted together with lines indicating different factors of transmission loss. This approach can give a useful estimation on what the effect of the transmission loss is.

In Figure 6.4 the received sound levels are plotted together with lines indicating two transmission loss factors, 18 $log(r)$ and 40 $log(r)$. The figure indicates a transmission loss which is significantly higher than 18 $log(r)$, which is the transmission loss specified by the *Silent Class*-notation [2]. The sound levels decay at a rate higher closer to 40 $log(r)$, which is the transmission loss which can be found when considering the Lloyd Mirror Effect as discussed in Section 2.1.5 and [8].

This inconsistency should be considered when performing and processing measurements used for classification of vessels according to the standard. The transmission loss can vary from location to location due to for example bathymetry or other factors. An idea to deal with this problem could be to use this algorithm to make a better estimate for the transmission loss for distance corrections of the measurements. This could be done by smoothing the lines of these plots and finding the average decay of the sound levels and compare this to different transmission loss factors. This would lead to a better estimate of the radiated sound levels at the reference distance of 1 m. However, the *Silent Class*-notation is intended to handle measurements on shorter distances, so in that case it can be a better estimate for the transmission loss.

6.3.3. Sound levels and the auditory threshold

This metric is describing the distance at which the vessel is audible to the fish. As described in Section 6.3.1 some findings might be disregarded, but when comparing

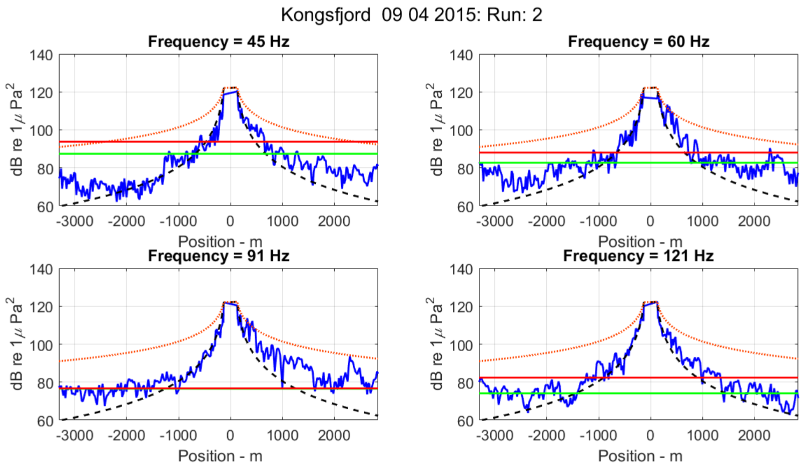

Figure 6.5.: Four of the most prominent frequencies radiated from Kongsfjord at different distances. The red line indicates the auditory threshold for haddock and the green is cod.

more plots the pitfalls can easily be avoided. In figures 6.5 and 6.6 four of the most prominent frequencies are plotted together with the auditory thresholds for cod and haddock. Kongsfjord is audible to fish at longer distances than Vesttind. The frequency component with the longest range for Kongsfjord is the 1/24-octave band centred around 91 Hz. At this frequency, the auditory threshold for cod and haddock are nearly the same. The sound level is at about the same strength as the auditory threshold up to 3000 m distance before passing the hydrophone, and it is higher than the audible threshold to over 2500 m after passing. For 121 Hz the difference between the two species is at its greatest for the shown frequencies. For haddock, it is audible at distances under 1 km. While for the cod it is oscillating around the threshold up to about 2 km.

Vesttind is more quiet than Kongsfjord, the most prominent peak of the vessel is at 102 Hz. This is audible from about 1000 m before passing until 1500 m after passing. When comparing the distances between the two vessels the difference around 1 km, which can also make a difference in the catches of fish they can generate.

Figure 6.7 shows the other approach. The sound levels is here referred to the auditory threshold of the cod. When the sound level is under the threshold no sound level is plotted, this causes the plot to be in-continuous. The advantage is the possibility to plot more frequencies in the same plot, to easily assess which frequency is audible at the longest distance. The weakness of the algorithm is that due to the low distance sample rate, some distances at which the sound level is above the threshold are not visible because of the plotting algorithm.

This metric can also be helpful indicating which frequency components that are not audible at the measured distances. The minimum distances vary between the

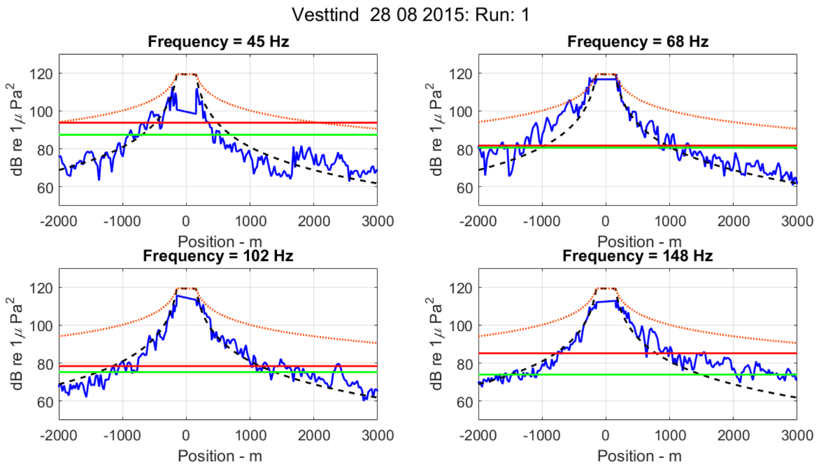

Figure 6.6.: Four of the most prominent frequencies radiated from Vesttind at different distances. The red line indicates the auditory threshold for haddock and the green is cod.

different runs, so the most weight should be put on the runs where the minimum distance from the vessel to the hydrophone is at its shortest.

6.3.4. Detection of Lloyd mirror minima

When studying the output from the LongRun algorithm, combined with the knowledge about the Lloyd Mirror Effect as described in Section 2.1.5. It is evident that there are minima occurring at lengths corresponding to the effect of negative interference. These minima can be verified to be results of the Lloyd Mirror Effect through comparison with a model. The minima are normally close to the source, this makes most of the minima caused by the Lloyd mirror effect impossible to identify, because for most of the runs the CPA was reported to be over 100 m. Figure 6.8 shows the single frequency line of 300 Hz together with the simulated propagation effects of a simple Lloyd mirror model and the Bellhop method which was briefly discussed in Section 2.1.7. In the Bellhop simulation and the Lloyd Mirror model, the source depth was chosen to be 6.7 m because this yielded the best agreement with the measurements.

Here the disadvantage related to a large minimum distance is evident. When the ship was passing the hydrophone, it was at least 150 m away from the hydrophone. The implication of the long passing distance is that the first minimum in the simulations is not recorded in the measurement. The Bellhop model is a simplified model with the same depth as was reported for the measurement of 90 m, constant sound speed of 1500 m/s and a sediment sound speed of 1650 m/s. The Lloyd mirror effect confirms the two first minima to be caused by the effect. The simulation accounts for the two minima yielded by the Lloyd mirror and it

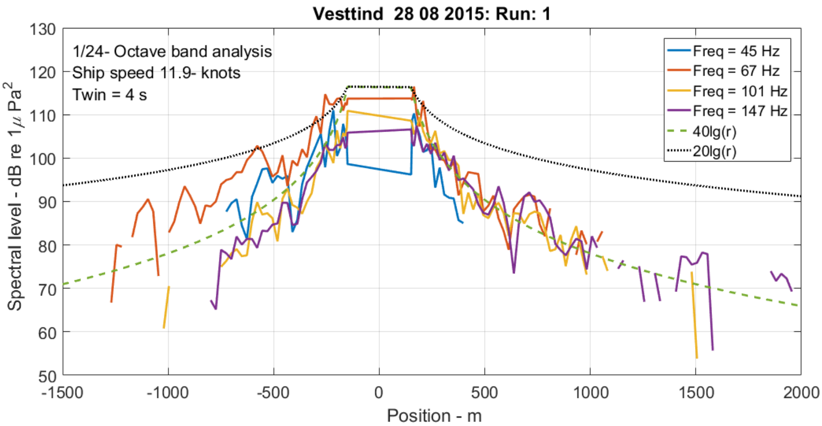

Figure 6.7.: The sound level of Vesttind referenced to the hearing threshold of the cod, at distances where there is no level indicated for a frequency means that this frequency is not audible for the cod at the given range.

shows a reasonable agreement to the measured values. However, as the distance increases the simulation shows evidence of minima but these are not as clear in the measurement.

6.3.5. Suggestions for best practice of measurements

To avoid *interrun interference* it is advisable to be sure to sail the ship out of the audible range or far enough to be able to separate the runs before returning the vessel for the next run. This is even more important when the vessel is trawling, when this is the case the speed is normally lower, causing the time needed to exit the audible zone around the hydrophone to take longer. It is also vital to assure that no other vessels come into the area which can cause disturbance and irregularities to the measurements.

6.4. TimeFrequency Matrix

The TimeFrequency Matrix is generated by a script that uses the same technique as LongRun. The measured signal is divided into segments with a short duration, for example two seconds. Through calculations including time of passing the hydrophone and the speed of the vessel the distance from the hydrophone to the vessel in each segment is found.

A maximum distance set, which serves as cut off distances for analysis. The maximum distance is calculated from the middle point, the CPA, as was defined in Section 6.1. The time at which the vessel enters and leaves the distance range used for analysis is found through calculations using the vessel speed and defined as T_1 and T_2 in Figure 6.1, and referred to in Figure 6.9 and 6.10. The segment used for

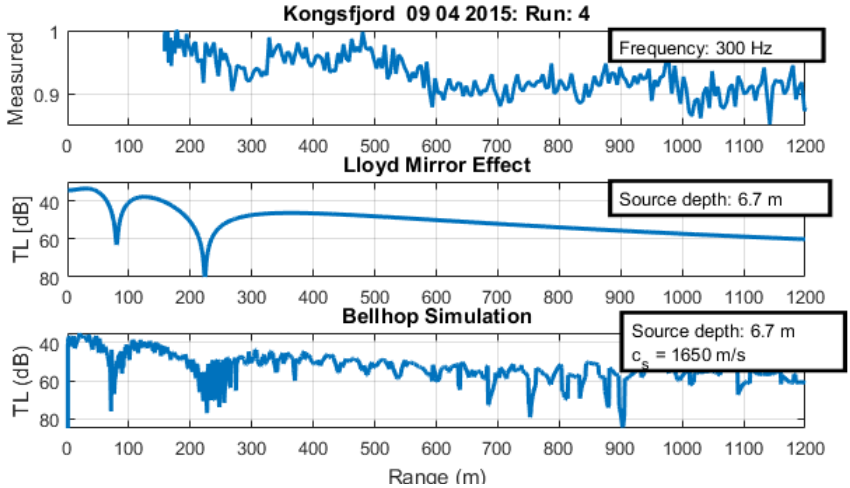

Figure 6.8.: Comparison between frequency line of 300 Hz from the fourth run of Kongsfjord to the same frequency simulated by the Lloyd Mirror Effect, as in Equation (2.8) and simulated with the Bellhop model.

analysis differs here from the octave band filtering according to the *Silent Class* which was discussed in Section 6.2 due to the length. In Section 6.2 the length of the segment was defined as close to 30 s, while it here is variable in time but defined in distance. Different vessel speeds will have an impact on the duration in time of the needed part of the measurements, this is done to make the results, such as Figure 6.9 and 6.10 comparable for vessels or runs with different speeds. Through a maximum distance for analysis, *interrun interference* can also be avoided.

The measurements inside the maximum distances are divided into shorter segments, each segment corresponds to a single line in the figures. The segments within the time span is Fourier transformed to find their spectra. The different spectra are indicating the radiated frequencies of the same vessel and are therefore almost identical, the difference is the recorded sound level. By introducing a threshold, all sound levels under this threshold is set to 0. This focuses the attention on the most prominent frequencies. When the spectra are plotted, an offset corresponding to the distance at which the segment was recorded is introduced. There is also a possibility in plotting the frequency spectrum against time shifts. The advantage in using distance instead of time shifts is decreased variability between plots where the speed of the vessel differs between the two runs. The amount of lines can be changed. When the lines are close enough to each other a fine pattern is created. This pattern can be helpful when identifying a vessel.

In Figure 6.9 the TimeFrequency Matrix-computed plot for Kongsfjord is presented. All values below a specified threshold is set to zero. This procedure makes sure that the irrelevant frequency ranges can be easily ignored. The harmonics from the propeller and main engine, see Sections 3.1 and 3.2, are clearly marked

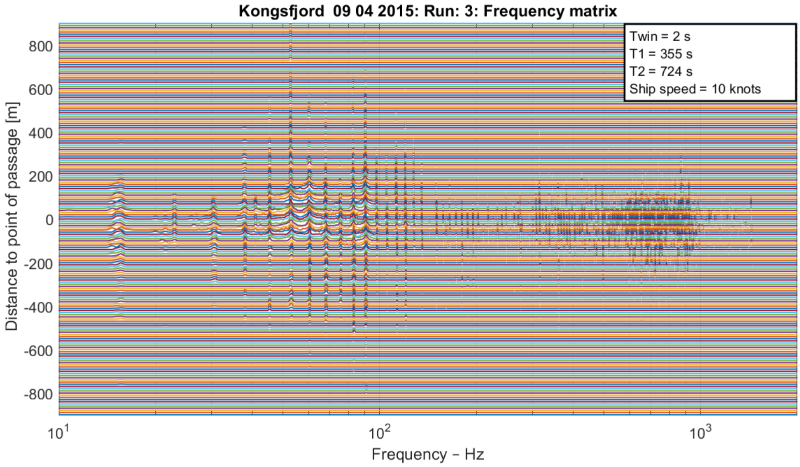

Figure 6.9.: The TimeFrequency Matrix generated plot of Kongsfjord showing the contours of its acoustic signature. T_{win} indicates the length of each segment, while $T1$ and $T2$ indicate the times when the vessel enters and leaves the relevant distance range.

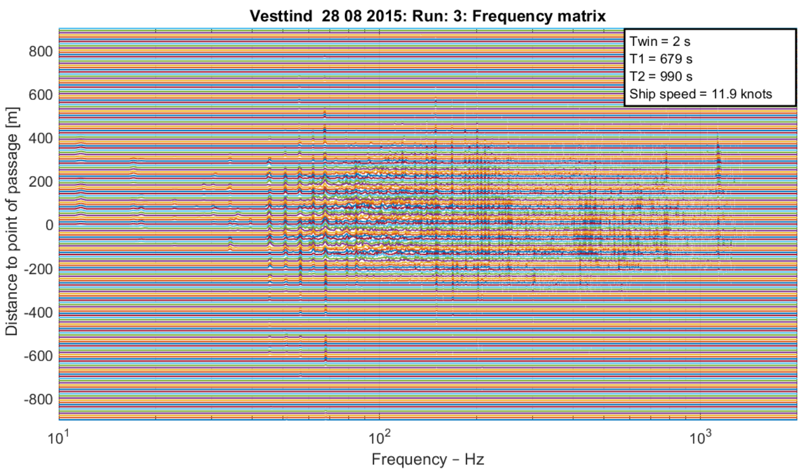

Figure 6.10.: The TimeFrequency Matrix generated plot of Vesttind showing the contours of its acoustic signature. The variables in the legend are the same as in Figure 6.9.

as lines that are apparent when receiving from many distances. These lines make the basis for the signature, or fingerprint of the vessel, the combination of these lines can be used to identify a vessel, therefore it can be very useful in military use-cases. For frequencies above a few hundred Hertz, the noise becomes more broad banded, and it is difficult to distinguish the peaks, the source of this noise is likely cavitation.

It is also possible to make a comparison between the radiation from the bow and stern aspect. When studying the line at about 15 Hz, it seems to be centred around 0 m, the point of passing the hydrophone, but there is also a smaller contribution at -400 m to -200 m, where negative distances indicate distance to the vessel before passing the hydrophone. While for example the line at about 60 Hz yields levels above the threshold at distances over 800 m after passing the hydrophone, while it is over the threshold only at about 500 m.

In Figure 6.10 the same algorithm has been run for the third run of Vesttind. It also has clear lines indicating the peak frequencies that has been discussed earlier. When comparing the two plots, Kongsfjord seems to have more clear lines especially for lower frequencies under $30 - 40$ Hz, this means that there are fewer frequencies with sound levels exceeding the threshold which has been set. The distances at which the sound levels are exceeding the threshold is also shorter than for Kongsfjord. This is in agreement with that Vesttind is a generally more quiet vessel than Kongsfjord as was discussed in Section 6.3,

6.5. An approach for measuring a vessel's directivity

It is well established that the directivity of a source is bound to the relationship between the size of the source and the wavelength. Low frequency sound has longer wavelength, λ, as in Equation (6.5).

$$f = \frac{c}{\lambda} \tag{6.5}$$

When the source size is small or comparable to the wavelength, the radiated noise will be omnidirectional. However, when the frequency increases, the wavelength decreases. So, the higher frequencies are more likely to have a higher directivity.

A hypothesis is that the lower frequencies do not change in sound level with direction. But the higher frequencies are louder in the aft of the ship, due to sound radiation through cavitation, which takes place at the propeller. This sound might be attenuated by the ship hull in the forward direction. From a fishing vessel's perspective, this is a good thing. As the goal is to catch fish that are in front of the vessel, backward radiation is expected to not be as influential on the size of the catches.

At lower frequencies, the directionality of the radiated noise might be affected by hull modes. This can happen for example if one of the natural frequencies of the engine overlaps the frequency of a hull mode.

6.5.1. Observations from literature

Most of the work that has been done on ship noise is more theoretical and real measurement data of ship radiated noise is not too common. In those cases, where data is available and has been described, the overall sound level is in focus. The directivity is normally at most shortly mentioned in passing and more as a bi-product of the data analysis and not the main focus. In many cases, the directivity is not essential. Ship noise is a topic in focus in regards to ecology and marine life. Here the overall emitted sound level is in focus. When the application is military or fishing, the directivity is more important. In [1], Arvesson and Vendetti found that in the forward and backward directions of the ship, at the frequencies dominated by cavitation there was less sound radiated. This was said to be due to blocking of the hull in the forward direction and in the backward direction the sound was attenuated by the bubbles resulting from the cavitation. The directivity in the blade rate frequency was also found to be omnidirectional. In [14], McKenna argues that there is more power radiated from stern aspects than from the bow, it was found that the difference in received levels amounted to $5 - 10\ dB$. These findings are somewhat in agreement with Jensen [9], who found through simulations that at higher frequencies the sound tends to radiate backwards. While at lower frequencies the hull has no influence, and the radiation is omnidirectional.

6.5.2. Data processing

The sound measurements of the fishing vessels were recorded as the vessels were sailing past the hydrophone. The data therefore do not contain information about the radiation in all 360 degrees. However, it contains data from almost 180 degrees. The directional angle to the hydrophone from the ship was found by estimating the distance by taking the speed of the vessel into account in addition to the time of passing the hydrophone. Figure 6.11 shows how the measurements were performed and how the angles required for the polar plot were found. On top the hydrophone is shown. The rectangle indicates the vessel at the different positions and the arrows indicate the different directions that were sailed in the different runs.

There are some drawbacks to this procedure, firstly the measurements where the angle is at its highest are done when the vessel is further away than when it is passing by the hydrophone at the CPA. The distance difference manifests itself in a decreased level at the larger angle. This is compensated by adding an estimated transmission loss corresponding to the distance. However, the transmission loss will vary across sea conditions and frequency. The transmission loss that was used was $18\ log(r)$, which is the standard in the *Silent Class* [2]. Other known transmission loss coefficients were considered, these had different contributions as the distance increases from the location of passing. But as the *Silent Class* standard is $18\ log(r)$ and it is a good estimation compared to the other factors that were considered. $18\ log(r)$ was used for calculations for all frequencies. This makes it problematic to draw conclusions with measurements from different distances and is something that needs to be improved to make this procedure a correct analysis of directionality. Secondly, the angle increases more slowly at larger distances than

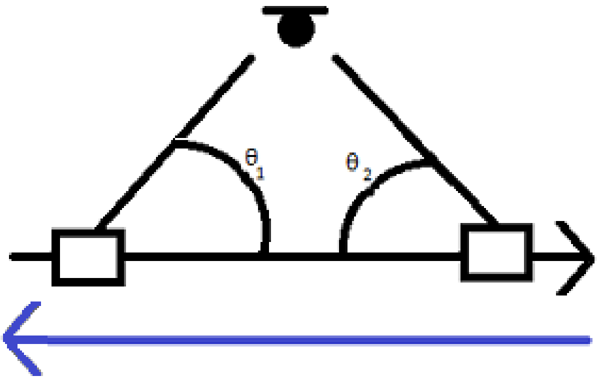

Figure 6.11.: Drawing which shows the measurement procedure and how data from the different angles were found.

at shorter distances. This will yield more fluctuations in the levels in the forward and backward directions and due to less sample points at smaller angles, smaller changes in the levels might not be captured.

The algorithm is based on LongRun, which was described in Section 6.3. The maximum length which is used here is approximately four seconds, and this is indicated in the figures. Each of these segments are Fourier analysed, and octave band filtered. The distance from the ship to the point of passing the hydrophone is calculated by making use of the speed of the ship as well as the depth and the time when the maximum sound level occurs. This exact time is used as basis for calculating the time of passing the hydrophone. Through these procedures the distance to the time of passing may be found. By using Pythagoras' theorem the last edge of a triangle can be found, the hypotenuse of the triangle is the distance from the ship to the hydrophone which is used to calculate the transmission loss. With all the sides in the triangle are known, the angle, θ is found by using basic trigonometric principles, as shown in Equation (6.6):

$$\theta = \tan^{-1}\left(\frac{x}{y}\right) \tag{6.6}$$

where x is the distance from the ship to the CPA, and y is the distance from the CPA to the hydrophone itself. The theta is shifted by $\frac{\pi}{2}$ to yield the results shown in Figure 6.12 and 6.13.

When this procedure is calculated for each run, the resulting angles are between $0°$ and $180°$. Through running this procedure two times, with two consecutive runs, data from almost all directions will be gathered. Only the two extremes at the forward and aft prospects are missing. These parts of the data are difficult to gather through this procedure. It is possible to get closer through sailing further away from the hydrophone. But then the data quality will be deteriorated because of a lower signal to noise ratio as well as increased uncertainty in transmission loss as a consequence of increased distance.

It is crucial for the analysis that the time of the ship passing the hydrophone is correct. If not, the results will be heavily skewed in one direction. In addition to the errors in angle not being correct, the compensation for the transmission loss will increase the error. This error factor is also dependant of the speed of the vessel. With higher speeds, an error in time has larger effects for the distance and the angle accordingly.

6.5.3. Results

The frequency spectra of each of the ship recordings show clear peaks at multiples of the blade rate, main engine firing rate as discussed in 3.1. It is therefore of interest to look at the directivity of these specific lines. In this way, it is possible to follow the spectral lines of the radiation originating from the propeller or the main engine. If the ship hull plates do not influence the radiation the radiation from for example the engine would be stronger from the aft of the ship, where the main engine is located. If the radiation is spread more evenly, this can imply that the vibration from the main engine is spread mechanically through the structure of the ship and excites vibrations in a larger part of the ship, spreading the sound radiation into the sea to a larger area. Another finding that indicates heavy influence from plate vibrations is that some of the higher harmonics of the main engine firing rate have more energy than the first harmonic. An explanation for this might be that the higher harmonic coincides with a resonance frequency of the ship plate, which causes the stimulus from the main engine vibration to yield excessive plate vibration resulting in higher radiated pressure levels.

Frequency of the blade rate

The first harmonic of the blade rate is located at or about $10 - 11\ Hz$ for the different ships, this is the lowest frequency of the harmonics. Sound with low frequency has less decay with distance. By compensating for the transmission loss with the same values as for higher frequencies might yield excessive for long ranges. A measure to deal with this effect is to set a maximum range that is used in the plot to ensure reasonable results. In this case the maximum range was set at 600 m, this distance yields a reasonable range of angles. In Figure 6.12 the polar plots for the blade rate frequencies of Kongsfjord and Vesttind are shown.

There are minima that are occurring for both vessels, both in odd and even runs. Both vessels have minima at about 180° and between 180° and 210°. While the minima at the corresponding angle, 30°, at the same distance before passing the hydrophone is clearer for Kongsfjord, especially for the first and fifth run. While for Vesttind the sound level seems to be lower at the angles between 300° and 60°. However, a trend specific to Vesttind is the strong noise components in the aft direction, this is not found for Kongsfjord, on the contrary for two of the runs, the highest level is located closer to the bow aspect. A run that stands out is the second run of Vesttind which distinguishes itself as omnidirectional. However, this run has the highest recorded speed of the runs of the two vessels. This effect might be because of a wrongly recorded speed. If the recorded speed is higher than what

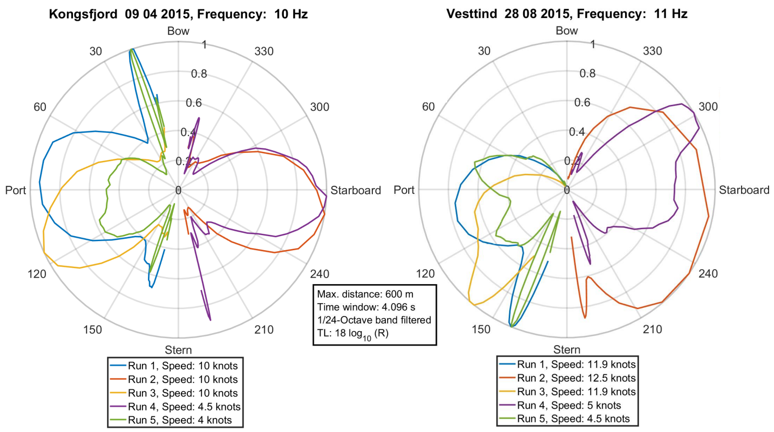

Figure 6.12.: The generated polar plot of Kongsfjord and Vesttind in the frequency of their respective blade rates.

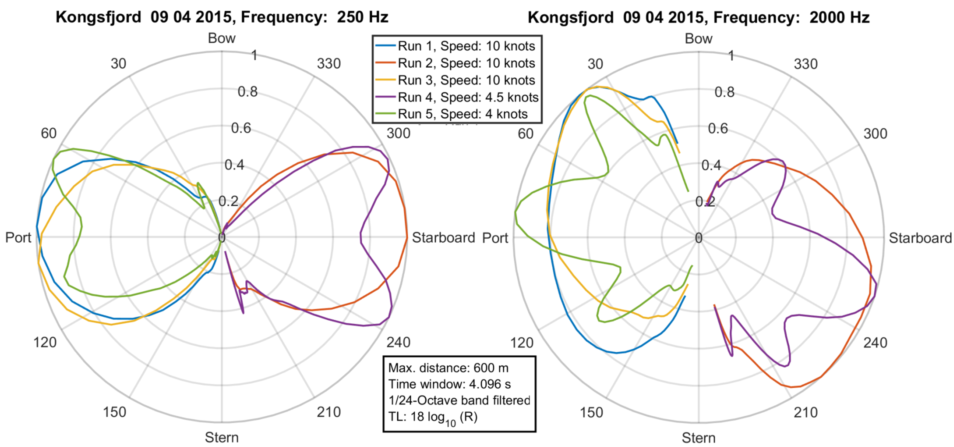

Figure 6.13.: The polar plots of Kongsfjord at 250 Hz and 2000 Hz, it is clear from this figure that there is variability in the measured values for the two slowest runs, which are those with the trawl.

it actually was, this would be the effect, the same lobe that is apparent for the other runs would be spread out with wider angles.

Other observations

The rest of the frequencies that were looked at seems to be close to omnidirectional with a trend towards more sound radiated in the stern aspects. However for Kongsfjord the runs with the trawl out seemed to have more variability, this was the case for 250 Hz and 2000 Hz. The speed for these runs are lower, this causes the sampling rate versus distance and therefore angle to be higher. This effect is shown in Figure 6.13.

Another observation that can be made from Figure 6.13 is the difference in the maximum of run 4. For 250 Hz, the two maxima are centred around 270°, while for 2000 Hz it is shifted closer to about 250°.

7. EcoNoise and the graphical user interface

EcoNoise is a program written in Matlab by Jens Martin Hovem. It calculates the frequency spectra of ships as specified by the DNV-GL's standard for the Silent class [2]. It consists of several functions, and a script that combines the functions and computes the ship noise as specified. As a part of this thesis a graphical user interface was developed to simplify the use of this program. The user interface was written in Matlab App Designer, and is based on object-oriented programming. The functions of EcoNoise needed therefore to be changed in order to be compatible with the App Designer.

7.1. Description of the EcoNoise Algorithm

The program is written to process the measurements as they are performed by Ecoxy. The files need to be in the same format as well as a file including settings corresponding to each vessel and run. This includes for example which time interval that should be processed and data describing the run. The main parts of the program for calculating the octave band filtered spectra are listed below

- EcoNoiseStartup
- FreqBandAna
- OctaveBands
- OctaveSettings

The script EcoNoiseStartup is the main file of the program. The files corresponding to each vessel is loaded. The main parameters such as the width of the octave band filter can be chosen. *FreqBandAna* is then run, this function calculates important parameters such as transmission loss compensation, the time window which should be used for the analysis, it also runs the function *OctaveBands*. When this function is run, an outtake of the signal where the signal is at its strongest is used as input. It also takes other inputs such as

- Estimated transmission loss for compensation
- Q-value (width of the octave band filter)

In this function the measured signal is Fourier analysed and filtered with an octave band filter with frequency bands specified by the *OctaveSettings*-function. The sound level values for each frequency band are then returned to *FreqBandAna* and plotted.

7.2. Graphical user interface

The graphical user interface was written with the App Designer functionality in Matlab, it was introduced with Matlab R2016a. The App Designer is getting more and more functionality with every new release of Matlab. The main difference between the programs written for the App Designer and normal Matlab scripts is that the App Designer uses objects. Therefore, the normal Matlab functions need to be changed to object-oriented algorithms. Some internal Matlab-functions are not yet supported. As an example, saving plotted figures is still not possible using the R2016b-release, this example is one of the functions that will be added when it becomes available in the App Designer. When opening the *app*, an object is created. Through the handling of the user interface the values of the object can be changed. There are also buttons present, these enable the user to run the included scripts. In the following flow charts, the rectangles indicate functions that are needed for the program to run while the diamond shaped squares indicate buttons that can be pushed. The arrows indicate functions that are run automatically when a button is pushed or run by another function.

7.3. Implementation of and using the GUI

The start-up screen shows four buttons. By pressing one of these buttons the user sets the GUI in one of several modes. Each mode is made to handle its own included function, such as the possibility to plot already computed files or to process the measurements and do the octave band filtering. The start-up screen layout is shown in Figure 7.1.

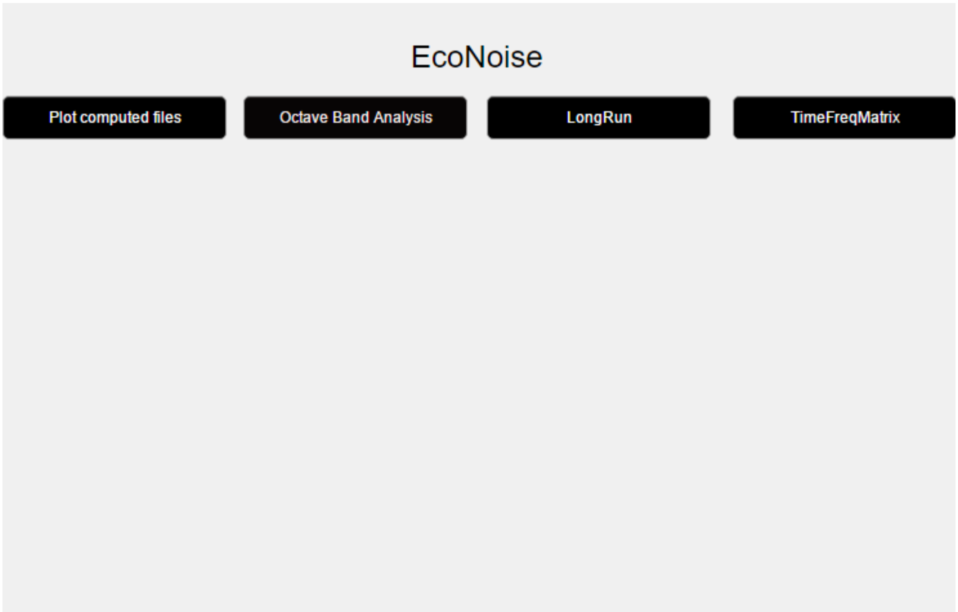

Figure 7.1.: The start-up screen of the graphical user interface developed for EcoNoise. A button for each function can be pushed to enter the interface belonging to each separate function.

7.3.1. Plotting the octave band filtered spectrum

The processed files from the different ships and their respective runs are saved when running the conventional version of EcoNoise. These files are what is being processed here. This is a practical possibility because running the conventional version of EcoNoise requires a lot of computing power and is time consuming, and when operating a GUI, the user appreciates fast responses in the computer program.

Figure 7.2 shows the flow chart for the functionality behind the functionality for plotting the stored frequency spectra. Single runs from one ship can be plotted, as well as a comparison of different runs from the same ship. By changing the value of the Q-value, the wideness of the octave bands can be changed, the possible values are here 3 and 24, and if the spectrum has been calculated with other filter widths,

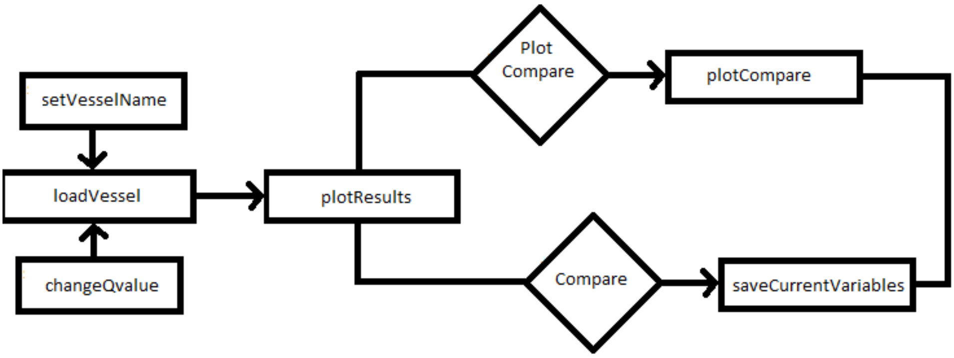

Figure 7.2.: Flow chart showing the structure of the functionality behind plotting the already computed files.

these are also possible to plot. When changing this value, the current plot will change into the same runs with the different Q-value. From Figure 7.2 it is evident that there is a possibility to compare different vessels. This is done by the push of two buttons, one to temporarily store the current plot and one to add the stored plot to the current plot.

7.3.2. The main function of EcoNoise

It is important to have the full functionality integrated in the graphical user interface. Therefore, it is important that it is possible to run the octave band filtering on the files from the interface. A new feature that was added here was the possibility to search for vessels in a search bar. This makes it possible to use the program to process measurements of new vessels. Figure 7.3 shows a screenshot of this mode of the interface and gives an indication of how the interface is used.

The flow chart is shown in Figure 7.4. This has a more complex structure than what was needed in the last section, as in Figure 7.2. The line *if(newFileName* indicates that this arrow will only be followed is the filename that comes up is unknown, indicating that the file has not been processed before. The processing takes place in the function *FreqBandAna*. The process to save the results is what is adding the most to the complexity of the program compared to plotting the already calculated files. The label *if(newFileName* indicates that the function *setShortFileName* is only run when the file that is processed has not been processed earlier and is new to the library. This is checked by comparing the name of the filename with the files that have already been saved.

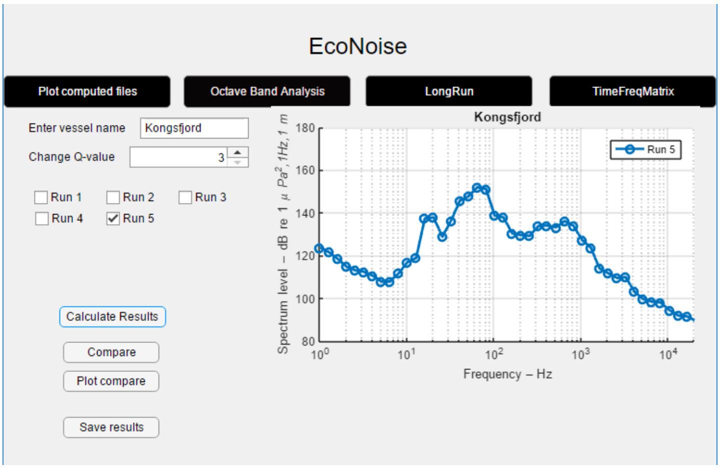

Figure 7.3.: Screenshot of the graphical user interface in the mode for octave band filtering.

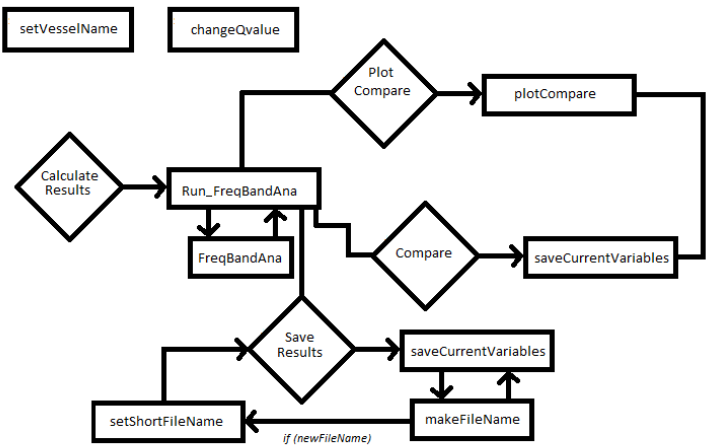

Figure 7.4.: Flow chart showing the structure of the main program for calculating the spectra.

7.3.3. TimeFrequency Matrix

This part of the program is implemented similarly to the stand-alone script in that there are no additional functions. It is the function with the least options. The only thing the user can choose is which vessel to analyse and which run. This function can only handle one single run simultaneously. This can be seen in Figure 7.5 which shows a screenshot of the graphical user interface in the mode for running the TimeFrequency Matrix-algorithm.

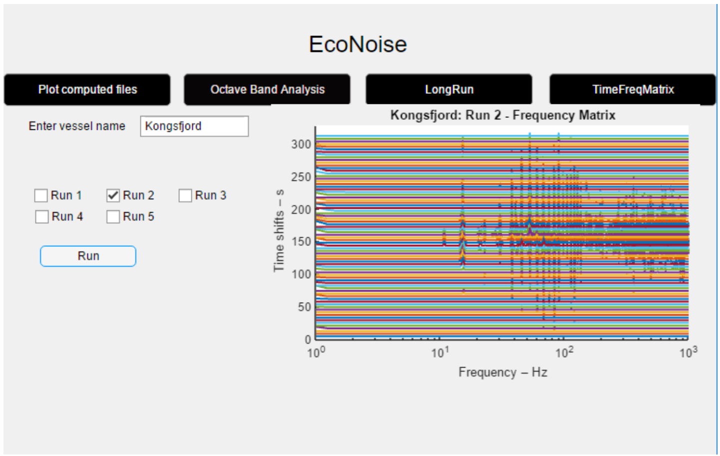

Figure 7.5.: Screenshot showing the GUI in the TimeFrequency Matrix-mode.

In Figure 7.6 the flow chart is shown. TimeFrequency Matrix has the simplest functionality out of all the functions. The user chooses only which vessel and run to analyse and the main function is ready to be run.

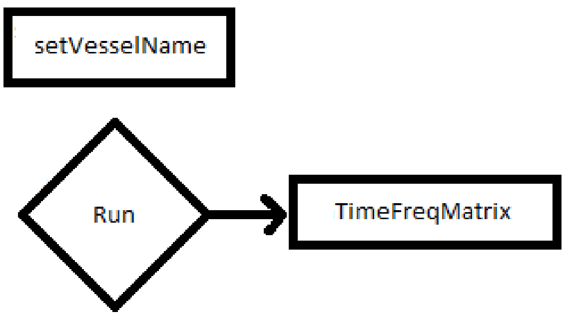

Figure 7.6.: Flow chart showing the structure of the functionality to run the script TimeFreqMatrix.

7.3.4. LongRun

This function is based on following specific frequency bands over different distances. It is therefore essential that user can select which frequencies to follow. This is done by adding one frequency at the time, which adds the frequency band in which this frequency is located to an array which stores the frequency bands that will be plotted. The user can also delete the set frequencies by pressing another button. Which run to plot and the width of the octave band is set as in the other functions. Figure 7.7 shows a screenshot from the GUI in the LongRun-mode.

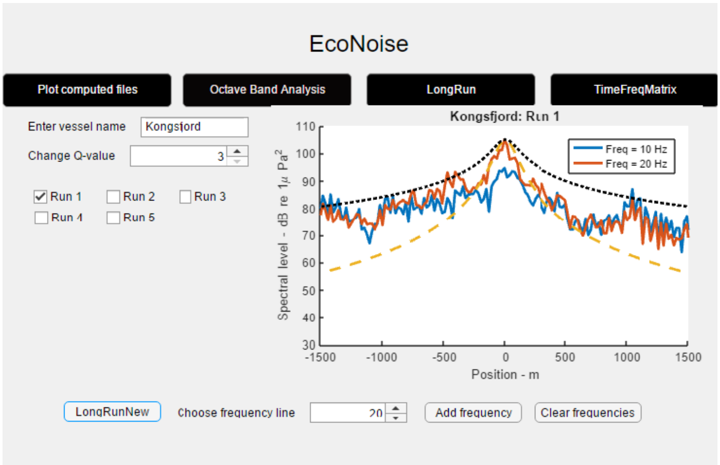

Figure 7.7.: Screenshot of the graphical user interface in the mode for running the LongRun-algorithm.

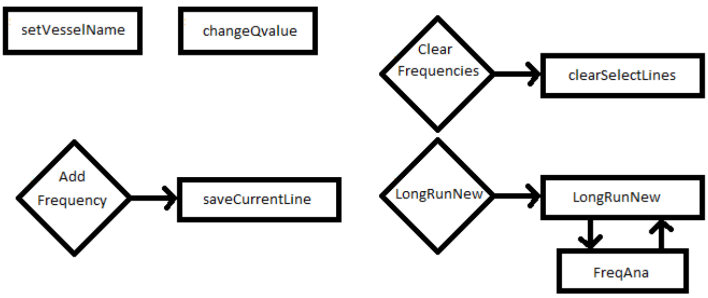

Figure 7.8.: Flow chart showing the structure of running LongRun from the graphic user interface.

Figure 7.8 shows the flow chart of LongRun. There is no complex network of functions. Each button runs one function. The exception is the main function, *LongRunNew*, which runs the function *FreqAna*. This is where the Fourier analysis is done. *FreqAna* returns the data needed to plot the results, and it gets plotted from the function *LongRunNew*.

7.4. Further work

This is an early version of a graphical user interface for the EcoNoise program package. There is still a lot of functionality that can be added. In the future, it would be ideal to make it even more user friendly. As the program output are plots, when the functionality to save figures directly from the GUI, this is a function that should be added.

The ultimate goal is that it can do live recordings and process the data in real time. For this to be feasible several problems must be solved.

- Distance from hydrophone to vessel to compensate for transmission loss
- Transfer of data and data buffering

The distance from hydrophone to the vessel is possible to find with the help from AIS, or GPS. With a combination of these services, the measured data can be bundled with GPS-coordinates and AIS-data. This could be used to automatically find the minimum range and accurate positions in between which the radiated noise should be used for the analysis. When looking away from the possibility of real time analysis the data buffering would not be a big problem, it is likely that a time lag in the computation would have to be accepted due to the time needed to process the data which will happen locally after receiving the data.

If this could be implemented, the fishermen themselves could assess the yielded data and make changes in how they operate the vessel or see the impact that different operation conditions can have on the radiated noise. With the proposed procedure it could be possible that the operator of EcoNoise can have results calculated soon after the measurements have been performed but not in real time.

8. Discussion and conclusion

The motivation for this study was the increasing interest in marine anthropogenic noise sources, and ships specifically. The main focus has been to draw conclusions about the relationship between ship radiated noise and its implications on marine life, with a focus on fish.

The study has reviewed the required knowledge for calculating underwater sound propagation. Ship noise and the different origins of ship noise has been discussed. It is vital to understand the mechanisms of noise generation to be capable of minimizing the emitted sound level. Different ways of characterizing ship noise have been presented. The measurements that have been analysed were performed according to standardized procedure in the rules of the *Silent Class*-notation. The measured data was also used in different ways to characterise the radiated noise in different ways. An approach to identifying vessels has been described as well as finding out at which distance specific frequency components of ship noise become audible to the fish. Based on one of the algorithms, an approach for measuring the directivity of a ship's radiated noise was described. The approach yields reasonable results, but it has weaknesses in the propagation effects that arises with compensating for the transmission loss for measured values at different distances due to variability in the transmission loss factor. A graphical user interface was also developed to combine the functionality of all the smaller functions. This was done to make the functionality more user friendly and more accessible for people with deep technical and programming knowledge. To examine the relationship between the emitted noise of the ship and the ship hull vibration, the vibration of the hull of a ferry was measured. The vibratory resonance frequencies of plates of different dimensions were simulated to comment on the effect of changes in the dimensions to the resonance frequencies and densities of the modes.

Implications of the findings

The propulsion system of ships are generating low frequent tonals in the audible hearing range of fish and other types of marine life. While broad banded cavitation acts like a noise floor of the radiated noise in the frequencies where no clear tonals are present. These tonals are essential for identifying a vessel, as well as being the most important to measure and control regarding the noise limits set by the Silent Class-notation. When measuring the received sound levels of these frequencies at different ranges, it was found that sound with the strongest frequencies was audible for fish at distances between $1000 - 2000$ m, even over 3000 m in some cases. There was no clear difference in the results between the runs with and without the trawl in the water. The distance at which the fish can hear the vessel is a metric which is easy to understand, and can be used when comparing radiated sound levels between vessels, and useful as a value describing the sound level.

Approach for measuring a vessel's radiation directivity

A suggestion for an approach to measuring the directivity of the noise radiated from a ship was developed. It requires the vessel to sail past a hydrophone twice, one time with the hydrophone at starboard and one at port. It yielded reasonable results. For most frequencies the radiation was omnidirectional, but more power was found to radiate in the stern aspects. For some frequencies the runs with the trawl in the water seemed to radiate more in some directions than others. However, there are some drawbacks, it requires a comparison between sound levels compensated for transmission loss at different distances. This is hard to estimate over a vast range of distances. It is also vulnerable to propagation effects, such as the minima and maxima caused by the Lloyd mirror effect.

Vibration of the ship hull

The ship hull is a contributor to the radiated acoustic noise. The hull consists of smaller plates with vibrational resonance frequencies in the frequency range where the tonals that are apparent in the high-resolution frequency spectra. The modal vibrations of the ship plates are induced by vibrations from the mechanic equipment on board the ship, such as engines as well as flow noise stemming from the water passing by. Controlling for vibration is therefore an important part of controlling the emitted radiated noise. The vibration of the hull was measured in a ferry. The results showed peaks in multiples of the firing rate of the main engines, and other resonances which also were in the audible frequency range of most fish. Strong contributions in the audible frequencies were also found for the simulated plates with different parameters.

Fish reacting to ship noise

Ship radiated acoustic noise is audible to fish. However, it is vital to know more about how the fish reacts to the noise. This can be helpful when suggesting regulations as well as for the fishing vessels, so they can know more about the implications of the noise they radiate.

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Appendices

A. Description of functions used in the GUI

Here a list and description of the functions that are used in the graphical user interface follows. There are more subfunctions needed to run the GUI, but they are not important for understanding how the implementation is done. The function name is listed, in parenthesis the modes of the GUI in which the subfunctions work are listed.

setVesselName (All main functions)

This function is run to change the vessel name-property of the object that is created by the app, and is therefore needed in all the different main functions, such as LongRun etc.

changeQvalue (Plot Computed Files, Octave Band Filtering, LongRun)

This function is run to set the wanted Q-value of the object. The function is needed in all usecases except in the TimeFrequency Matrix, because TimeFrequency Matrix is the only main function where no octave band filtering is done.

loadVessel (Plot Computed Files)

This function is run when the vessel name has been entered and loads the stored files containing the spectra of the vessels. The function runs *plotResults* when the correct files are loaded.

plotResults (Plot Computed Files)

This function is used when plotting the stored files containing the frequency spectra of the vessels. It loads the files and plots them according to the current settings.

saveCurrentVariables (Octave Band Filtering)

Pressing the compare button runs this function. It saves the values that are currently plotted locally. Running this function does not immediately make changes to what is shown.

plotCompare (Plot Computed Files, Octave Band Filtering)

After pressing compare and running the function *saveCurrentVariables* the previous plot has been saved. Before pushing the button **Plot Compare** the user need to find other results to compare with. When this has been done, this functions loads the results that were save using *saveCurrentVariables* and plots the latest plotted results on the same axes. When the button **Plot Compare** is pushed it also saves the current plotted results. In this way it is possible to plot more the results of more than two vessels in the same plot. It is also possible to compare different widths of the Q-value. When the Q-value is changed, it is only possible to compare maximum two vessels at the same time.

Run_FreqBandAna (Octave Band Filtering)

This function is run after pushing the button **Calculate Results**. It loads the file containing the measurements and initializes the needed variables for running *FreqBandAna*. Which is run from this function.

FreqBandAna

This function is the same as the original, the input from *Run_FreqBandAna* has been modified to the algorithm. The functionality was discussed in Section 6.2.

saveCurrentVariables

If the user wants to save the calculated results this is done by pushing the button **Save Results** which runs this function. The filename to be used is found by running the function *makeFileName* which returns the name.

makeFileName (Octave Band Filtering)

This functions compares the current filename to the filenames that have already been processed. If the vessel name has not yet been included, instead of saving the file it generates new fields where a string of letters can be set. This will serve as the new short filename. To save the new filename, the user must push the button that appears and then push **Save Results** a second time. To save the calculated results with the new wanted filename.

setShortFileName (Octave Band Filtering)

If the filename is not already known, the fields where the new filename can be specified will be saved by the push of a new button, which will run this function.

TimeFreqMatrix (TimeFrequencyMatrix)

This function initializes the function is run by pushing the button **Run**. The functionality was discussed in Section 6.4.

saveCurrentLine (LongRun)

This function is run when the button **Add Frequency**, it requires an integer to be specified in the corresponding field. This number will be added to the array of numbers which corresponds to the frequencies that will be tracked over distance. The frequency itself will not be tracked, but the frequency band that contains it will be tracked.

clearSelectLines (LongRun)

This function is run when the button **Clear Frequencies** is pushed. Pushing this button will delete the variable that contains the frequencies that will be tracked. This enables the user to track different frequencies than what was initially intended.

LongRunNew (LongRun)

LongRunNew will be run after the button with the same name is pushed. This function is close the original, but it was customized to fit the object-oriented needs of the Matlab App Designer. It runs *FreqBand* which returns the needed variables and plots the sound level ogf the different frequency bands at different distances. The functionality was discussed in Section 6.3.

FreqAna (LongRun)

This function is where the processing of the LongRunNew-algorithm takes place. It takes input from *LongRunNew* and processes the measurements such as discussed in 6.3.