The Quiet Ship

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Management summary

The research started with a literature study to get knowledge of the subject. This resulted in a problem definition which is: Vessels nowadays have to comply with new legislation from the IMO to reduce the sound the vessels make to protect marine life that is severely affected by the loud noise.

To solve this problem a main question was created: In what way can the vessels be silenced to comply with the IMO legislation. To answer this question the research had to be divided in sub questions.

The first sub question was created to get to know what the exact legislations are and what they will be. What are the new IMO rules concerning ship noise? A large part of this chapter is desk research, however also field research was required to answer this question. There has been spoken with Mr. de Leeuw to complete the research. Mr. de Leeuw is a teacher of the Rotterdam Main Port University and is specialized in Maritime legislations. After those processes there can be concluded that the new IMO rules consist of non-mandatory guidelines to reduce underwater noise. The measuring system for a universal standard has been accepted by the IMO. The legislation with specific levels of noise cannot be made yet, because of the lack of research.

The second sub question is about the exact noise sources, to know where the problem come from. So the question is; ‘What causes the noise emitted from vessels’. The desk research served as a start for the understanding of the theory. To get an answer on the complex aspects of the subjects, interviews with two companies, Rubber Design and MARIN were held. All of this resulted in the conclusion: Cavitation and vibration are the main sources. They depend on the speed which is the biggest noise source. Above approximately 12 knots cavitation is the biggest noise source, below 12 knots the vibrations creates the biggest noise.

In the last sub question; ‘In what way can the noise be reduced?’ is find out what practically feasible solutions could be. In the desk research phase the existing solutions are viewed, however the biggest part consist of field research and is also made possible by Rubber Design and MARIN. This result in the following conclusion: There are a lot of ways to reduce the noise produced by vessels. Slow steaming and diesel-electric are the best two existing solutions.

To make this project innovative, the decision to come up with a own solution: the bubble curtain, which is tested in an experiment was taken. The inspiration of this subject came from drilling platforms which also use a bubble curtain to reduce the noise pollution. After doing the experiment and comparing the result, there could be concluded that the result also confirm on a proceeding vessel.
Preface
This report has been written for the Maritime Symposium 2015 at STC Rotterdam

Our research is about a rather new subject in the maritime sector: Silencing ships. There has been a lot of research done in the field of silencing a vessel to make it more comfortable for the people on board of the ships, but little research in the field of protecting sea life for noise produced by vessels.

We decided to tackle this problem and find out what we can do to make the oceans quieter and safer for marine life.

When we did our research there were the usual bumps in the road, but we were determined and eventually we achieved our goals and we really think that we made a step to save the whales.

Of course we couldn’t have done this research without the help of experts from companies and organizations.
We all would like to say a big thank you for all of your help and support!

- M. van der Drift  RMU
- G. Blankenstein  RMU
- J. van der Pol  RMU
- J. de Groot  RMU
- W. de Leeuw  RMU
- P.C. van Kluijven  RMU
- ir. J. Bosschers  MARIN
- M. Klijn  Rubber Design

We hope you will enjoy reading about our research!

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Rotterdam, March 12, 2014
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1. Introduction

1.1 Backgrounds
This chapter describes the backgrounds of ‘The Quiet Ship’.

The research is inspired by the new legislation of the IMO regarding a maximum amount of noise that the vessels are allowed to. The vessels must comply with this legislation in the near future. Thus the stakeholders of our research are the shipping companies with vessels that do not comply with the new legislation.

1.2 Problem definition and project objective

1.2.1 Present situation:
The noise vessels create nowadays have a severe impact on the marine environment. Particularly the northern hemisphere regions experience an increase in low-frequency (<1000 Hz) noise. The sources of these noise are mostly the vessels used for our transport of goods around the world. The ship’s noise is created mostly by the cavitation of the propeller. Other causes are the wake created by the hull and the vibration caused by the machinery that is needed for the propulsion and the life onboard the ship (Inc, 2014)
Public awareness of how the noise affect animals is driven by dramatic but rare events like whale beachings following sonar events. Ship-emitted noise presents fewer obvious but continuous, broadly-distributed issues. These noise can affect marine animals in non-lethal yet significant ways, reducing communication ranges particularly for species reliant on low-frequency noise to socialize and navigate like sea mammals (whales, dolphins) and even fish.

1.2.2 Desired situation:
To preserve the marine life, the IMO has introduced new legislation. The vessels must comply with this new legislation within 15 years. The problem with this new legislation is that the current vessels do not comply with the guidelines set by the IMO, so to this problem a solution is required. There are several researches ongoing concerning noise reduction, but there is not a practical solution yet for existing vessels (Welfare, 2009)
Creating a solution to reduce the noise made by the vessels can be done in a number of ways, for example: noise cancelling, streamlining the hull, anti-vibration technologies for the machinery and new propulsion technologies. This solution needs to be highly fuel efficient, cheap in costs and installation, and compatible with all vessels in order to be installed on the ships. In other words, as efficient as possible. This solution must make vessels comply with the new legislation. The idea is to look into some existing solutions but also try to come up with a new innovative idea (Kregting, 2014)

1.2.3 Problem definition:
Vessels nowadays have to comply with new legislation from the IMO to reduce the sound the vessels make to protect marine life that is severely affected by the loud noise.

1.2.4 Project objective:
The main objective of this project is to come up with an efficient way to silence vessels, so that they will comply with the new IMO rules that come in effect within 15 years.
1.3 Project assignment

Keeping the project goal in mind, the main question of this research is: **How can the vessels be silenced to comply with the IMO legislation?** To answer this question, sub questions are formed:
- What are the new IMO rules concerning ship noise?
- What causes the noise emitting from vessels?
- In what way can the noise be reduced?
- How can under water noise reduction be demonstrated on a small scale, simplified experiment?

Research about the question ‘**What are the new IMO rules concerning ship noise**’ Has been done by consulting articles about the legislation of the IMO. The main information used from these articles are of a qualitative nature, because the sub question is about the specific rules in the legislation.

To answer the sub question ‘**What causes the noise emitted from vessels**’, the research has been either desk research or field research. The articles must be about completed experiments with noise created by vessels, and the information has a qualitative and quantitative nature. The field research has been done by interviewing experts on this particular subject or have done experiments.

Research concerning the sub question ‘**In what way can the noise be reduced?**’ Has been done by doing desk research about already created solutions for this question, using qualitative information, or by doing field research. Existing solutions are anti-vibration techniques, propeller and propulsion technologies, and streamlining the hull. The research will primarily focus on counter noise. This field research consists of interviewing ship builders, and researchers from TU Delft.

For the last sub question ‘**How can under water noise reduction be demonstrated on a small scale, simplified experiment?**’ a combination of field and desk research has been done. Field research consists of the experiment itself and desk research about the setup of the experiment. The experiment consist of the replication of noise reducing technology.

1.4 Project boundaries

For the project there will be boundaries, in the length and the width of the project. The length means where does the project end. With the width is meant the subjects that will be investigated.

1.4.1 The length,

In the length the boundary has been set at a prototype. The research is limit itself to pure theoretical research, this means that the recommendations made are purely based on research results and not on real life tests. If a solution is created, the question how it can be applied to the vessels has not been implemented in the research.

1.4.2 The width,

In the width the boundary has been set at the costs. With every solution there will be some operational costs and investments. These costs will be taken into account, but the main objective is the solution. On the question about the experiment, if an experiment is possible, the experiment has been done.
1.5 Report composition

The report is composed of several chapters. Each chapter elaborates the corresponding sub question and answers the question in its conclusion. The chapters are followed by an overall conclusion to answer the main question ‘In what way can the vessels be silenced to comply with the IMO legislation?’ The final part of the report consists of recommendations after conducting the research. The first chapter contains the explanation of the new IMO legislation. It also mentions the expectations made by sources. As in every chapter, it ends with a conclusion. The next chapter elaborates the causes of the underwater noise. This chapter separates several causes from each other in different paragraphs. The end of the chapter is the conclusion. The third chapter discusses new ways to reduce underwater noise. The chapter uses the same sources of noise that are explained in the previous chapter, and mentions the solutions per source. The conclusion consists of a comparison of the solutions. The final chapter is the experiment conducted by the project group. This chapter also states the measurements and conclusion of the experiment. In the conclusion of the report, all the conclusions stated in the chapters are combined into one final conclusion to answer the main question.
2. The new IMO rules concerning ship noise

As discussed in the above, vessels nowadays have a severe impact on marine life. In this chapter, all the legislation concerning the underwater noise will be examined. First, the current situation will be explained. The specifics will be explained in subparagraphs as well. Later the expectations of sources are stated. There will be a conclusion at the end of the chapter which answers the question ‘What are the new IMO rules concerning ship noise?’

2.1 The current situation on the legislation

The IMO has, due to the adverse impact on marine life, made the priority for more research on the subject, in order to create specific legislation, such as maximum levels of noise and in specific frequencies. It also supports member governments to submit propositions on this matter. Due to the absence of legislation on this topic, the Marine Environment Protection Committee (MEPC) has created guidelines to fill the gap. The guidelines also include a reference to the official standards for measuring the underwater noise. These standards have been created by the Accredited Standards Committee (ASC).

2.1.1 The MEPC guidelines.

The MEPC has accepted guidelines to reduce underwater noise. Those guidelines are not mandatory for vessels at this time. The plan of the MEPC is to make the guidelines, or other legislation, mandatory in the near future. The guidelines apply to all commercial vessels. Deliberate noise from sonar and seismic activity readings will not be included in the guidelines.

After consulting the Koninklijke Vereniging van Nederlandse Reders (KVNR), the documents concerning the IMO rules for underwater ship noise, were made available. It was made clear that the circulaire MEPC.1/circ.833 was created in cooperation with the Marine Environmental Protection Committee (MEPC), and accepted in the 66th session of the IMO MEPC assembly. The KVNR was actively involved with the making of this document. This document is a list of guidelines for merchant vessels. (Minkelis Van, 2014)

The guidelines consist mostly of general protocols, to eventually reduce the underwater noise. The guidelines specify even further by only selecting the main sources of the underwater noise. These include: propellers, hull form, onboard machinery and operational aspects.

The guidelines have ample suggestions on how a vessel should be built and gives examples on how proper maintenance can reduce the noise. But when it comes to existing vessels, the guidelines only mention that the designs should, if practicable, be added to the existing vessels. For specified information on the guidelines, see the complete document containing the guidelines in appendix (i).

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While the guidelines of the MEPC seem to focus on the future, the European Union (EU) has created a more present measure. This measure introduces the good environmental status. Through research done by the Marine Strategy Framework Directive (MSFD), the ambient noise peaks have been established at 63 Hertz and 125 Hertz. The idea is that vessels reduce noise in the bandwidth of 10-300 Hertz by three decibel within ten years, and by ten decibels within thirty years. (Leaper, 2014)

This reduction of underwater noise means a reduction of 50 percent within ten years’ time. And a reduction of 85 percent over the course of thirty years. (Hofstede)

This good environmental status is not yet established for a maximum amount of noise, because of the lack of research on what level of noise is harmful for the environment and if different environments have different harmful noise levels.
2.1.2 How to measure noise.
The noise of the vessels is measured by using an international standard. In the standard the way the noise has to be measured is elaborated. The standard is used to create a universal way to measure the noise from any vessel. This document mentions that the measurements need to be taken at a distance of 1 meter from the geometric far field. The measurements are recorded in one third octave band. This octave band consists of several frequencies. These measurements can only be conducted in deep water, since the sea bottom reflects some noise. This reflection will interfere with the measurements. This standard helps the IMO asses the noise the vessels create. This standard specifies the noise by source and category. The standard is an universal guide to measure the noise created by the vessels in deep water. This standard has already been accepted by the International Standardization Organization, or ISO. These standards have also been accepted by both the MEPC and the EU. The document title of these standards is ISO 16554. (Minkelis Van, 2014) While the standards are already accepted, research about harmful levels of noise is still underway.

2.2 Expectations
The expectation is that the legislation will only apply to the new vessels. If the existing fleet needs to comply with the upcoming legislation, it is expected that either the fleet needs to update their ships with new manners of noise prevention, or when reasonable adjustments cannot be made, a milder version shall apply to them. (Leeuw, 2014) A second expectation is that the manifestation of the legislation will be silent areas. These areas could only be accessed by vessels that comply with the legislation. The main focus of those areas would be around the harbors. (Bosschers, 2014)

2.3 Conclusion
The question of this subject was: what are the new IMO rules concerning ship noise? The new IMO rules consist of non-mandatory guidelines to reduce underwater noise. The measuring system for a universal standard has been accepted by the IMO. The legislation with specific levels of noise cannot be made yet, because of the lack of research. It is expected that the newly built vessels have to apply to the legislation, followed by the existing fleet within a certain time. But only if the amendments that need to be made are reasonable to execute.
3. The noise emitted by vessels

The vessels nowadays produce too much noise, this disturbs the marine life. In this chapter the main focus will be on the question, What causes the noise emitting from vessels? There will be a large group of noise sources, especially the main sources will be treated. In short, there will be a research to the main sources and the theory behind it.

The two main sources that will be descried are cavitation and vibration.

3.1 Cavitation

Cavitation is caused by the high speeds of the propeller. This means that at higher speeds there will be more cavitation. According to Bernoulli’s Principle, when the speed rises the pressure falls. The propeller can be divided in two sides: The suction side where the pressure is low and the pressure side where the pressure is high(figure 3.1). In this figure you see a propeller in which the ‘X’ is the propulsion and ‘Y’ is wheel effect, however the main reason for choosing this image is to show the high pressure side(left) and the low pressure side(right). At the low pressure side vapor bubbles occur, because with a low pressure the boiling temperature of the water drops. When the vapor bubbles go to the pressure side, the bubbles implode. This causes damage and a lot of noise. (Cavitatie, 2013) (TUDelft, -)

![Figure 3.1 the two pressure sides on a propeller.](image)

There are seven different types of cavitation which all take place on a different part of the propeller, as in the picture below.

1: Bubble cavitation, this type takes place on the middle of the blade.
2: Fleece cavitation which occurs on the top of the blade.
3: Blade root cavitation, this form arises between two blades on the root of the propeller.
4: Cloud cavitation, arise on the sharp side of the propeller.
5: Screw-hull cavitation, take place on the upper side of the rudder.
6: Vortex cavitation. This runs behind the propeller.
7: Hub vortex cavitation which follows the nave.

For detail overview see figure 3.2. (Reducing underwater noise pollution from large commercial vessels , 2009)
The vortex cavitation and fleece cavitation are the two cavitation types which are the biggest contributors. This is noticeable in the practice, however this is not scientific proved.

Cavitation depends on the vessel’s speed. A higher speed results in more cavitation. When the propeller has a higher rotation speed, the pressure differential between suction side and pressure side will increase. However the increase of the pressure differential causes the propulsive force. There are different propeller sizes and for a larger one, less energy is required for the same proceeding speed. This means that with a larger propeller, less cavitation will occur, but the efficiency drops. So a balanced situation must be made. This will be further elaborated in the following sub-question. (Reducing underwater noise pollution from large commercial vessels, 2009)

Another contributor to cavitation is the flow of the water into the propeller. The underwater shape of the vessel causes a wake of the water which flows in a certain pattern into the propeller. This results in the increase speed of current, and in accordance to the Bernoulli principle this creates a pressure reduction. The inflow of the water causes a suction side, creating a side of the propeller where the pressure is extra low. At this extra low pressure side, the amount of imploding bubbles is increasing. Cavitation takes place at the upper side (figure 3.3) of the propeller. This can also be concluded from the above, because the inflow on the bottom of the propeller is more efficient. If it is decided to take a closer look at the inflow created by the hull, it is required to combine it with the propeller. So the hull and propeller are directly related. (Reducing underwater noise pollution from large commercial vessels, 2009)

The loading condition is also important for the occurrence of cavitation. The propeller is mostly made for a maximum load conditions. When a vessel is not loaded the upper side of the propeller will rise above the waterline. With most vessels this will result in more cavitation. Further information is elaborated in sub question four.
3.1.1 Hull design

The ship hull is important, because a streamlined hull creates less noise than a normal ship hull.

A badly designed hull creates an uneven wake flow which cause vibrations and underwater noise. Especially the aft end of the ship is important for the wake flow. The aft end of the ship creates the wake flow and this flow is crucial for ship propeller suction. When the aft end does not meet certain requirements, the wake flow creates more cavitation.

Fouling to the hull also creates noise. Due to fouling growth the resistance increases and causes turbulence, which creates more cavitation.

3.2 Vibrations

Besides the cavitation there are plenty of other causes which create underwater noise.

Cavitation causes definitely the loudest noise, but there is no reason to neglect the other noise creators, because that is part of the problem too. And below approximately 12 knots the engine vibration causes louder noise than cavitation. So the speed of the vessel is also an important part of the problem.

The biggest problem besides cavitation is the engine vibration. This vibrations creates a lot of noise and the noise goes right through the hull. Most of the (heavy) machinery on board creates vibrations. Those vibrations causes underwater noise. There are two types of frequencies: low frequency and high frequency. On board of vessels the low frequency is the biggest problem because of high energy level. This frequency is hard to muffle, because low frequencies does not absorb well. This results in a frequency that has a big range.

The four main sources which cause the noise are:

- The main engine creates vibrations
- Generator creates vibrations.
- Propeller shaft. Axial vibrations occur in the propeller shaft. There is also a chance that there are bending vibrations and distortion vibrations.
- Stern tube bearings

There is also a chance that resonance occurs. Resonance is that a vibrating object brings another object in vibration. Resonance occurs when a system is connected with a frequency equal to one of the natural frequencies. (van Maanen, 2000)

On board of vessels is the main engine the most sensitive for resonance. This is because of the vibrations the main engine creates. The generator also creates a lot of vibrations, but the most generators have a rubber foundation and rubber absorbs the vibrations. Rubber foundation is not possible by the main engine, because the propeller shaft must be kept in one position very precisely. The phenomenon resonance is for each ship different and it is a characteristic property. Which part of the engine room is sensitive the resonance is also depending on the ship. On board of sea going vessels resonance is not a very big problem as vibrating source. But there is a chance that resonance occurs on board. By example the ship foundation were the resonance may occur.
3.3 Operational factors
As mentioned before the speed is important for the emitted noise. The faster the propeller rotates the more noise is created by the propeller.

Maintenance can also be an important factor. When the maintenance on board of vessels is not suffice, indirectly it can create noise. It is important that the maintenance to the hull is good, when the maintenance does not suffice. There will be fouling on the ship hull which creates an uneven wake flow as mentioned before.

3.4 Conclusion
The sub question of this chapter is: what causes the noise emitting from vessels? There are two main sources which create the noise pollution. The first problem is cavitation, which is created by a different in pressure. This results in imploded vapor bubbles in which the noise creates. The faster the propeller runs, the bigger the pressure difference is. The ship hull is important because it creates a wake flow and this flow is crucial for the propeller suction.

The second problem is the vibration. Most of the machinery creates vibrations. Those vibrations go right through the hull and result in underwater noise. There are two types of vibrations, low frequency and high frequency. The low frequency has a higher energy level, therefore it can travel a longer distances. Cavitation and vibration are the main sources. They depends on the speed which is the biggest noise source. Above approximately 12 knots cavitation is the biggest noise source, below 12 knots the vibrations creates the biggest noise.
4. Ways to reduce noise

In the previous chapter, the conclusion was that there are two major factors causing the noise produced by a vessel: The propeller and the vibrations caused by the engine room. This chapter has been divided in two parts. In part one, the solutions for the noise caused by the propeller will be discussed. In the second part the main focus will be on the noise radiated from the engine room itself, especially the engines and the propeller shaft. To find ways to reduce the noise created by vessels, the sub question: “In what way can the noise be reduced?” will be answered in the conclusion. To answer this question a mix of field research and desk research has been used.

4.1 The propeller

In the chapter “The noise emitted by vessels”, the main source of the propeller noise has been discussed. In regard to that chapter the main focus will be on the reduction of cavitation. A cavitation free propeller is possible but it is extremely expensive to produce and not efficient. (Bosschers, 2014) Therefore it is not really useful for the merchant navy, because of the increase in fuel cost and therefore a lowering in profits. It is important to find a balance between the efficiency of the propeller and the produced cavitation. There are a number of ways to reduce the cavitation without reducing the efficiency significantly:

- Propeller design
- Regulating the flow towards and around the propeller
- Operational factors

4.1.1 Propeller design

As mentioned before, the design of a propeller has a major effect on the development of cavitation. Normally a propeller is designed to operate at a normal service speed, fully loaded in calm waters, but in practice a vessel will operate at different speeds and draughts, so the propeller is not always optimal for the conditions (Leaper, 2014). A way to prevent cavitation on and around the propeller is to change the angle of attack between the root and the tip of the propeller. This will result in a decrease of the differential in pressure between the tip and the root. Because of the lower pitch at the tip of the propeller, the difference in speed between the tip and the root is lower (Fig 4.1).

Fig 4.1 Angle of Attack and Blade Twist
Therefore in accordance with Bernoulli’s Principle, which states that “for an inviscid flow of a fluid, an increase in the speed of the fluid occurs simultaneously with a decrease in pressure or a decrease in the fluid’s potential energy” (Bernoulli’s principle, 2014) the pressure decrease at the suction side will not result in the formation of cavitation, due to the higher pressure the water can’t transform into vapour (Bosschers, 2014). A downside of this method is that the design and placement of a new propeller on current vessels is expensive and time consuming.

Another possibility to decrease cavitation is to increase the surface area of the propeller. With an increase of the surface area, the propeller will be able to move more water, resulting in an increase in speed of the vessel with the same revolutions per minute. Unfortunately an increase in surface area will make the propeller larger and heavier, creating an increase in resistance and production costs. Due to the higher weight of the propeller the maximum loading capacity of the vessel will decrease.
4.1.2 Regulating the flow towards and around the propeller

Equally as important for the development of cavitation as the propeller design, is the water flow towards and around the propeller. The flow around the ship’s hull is turbulent because of the fact that the flow around the hull is faster than the flow further away from the hull. This difference in speed causes a turbulent flow towards the propeller. By reducing this turbulent flow, the efficiency of the propeller can be increased. A vessel can be fitted with an ESD (Energy Saving Devices). ESDs can be fitted on the ship’s hull and regulate the flow towards, around and behind the propeller. The ESDs convert the turbulent into a more stable, controlled turbulent flow, resulting in lower propeller load and hence reduced cavitation. (Jong, -)

ESDs fitted near the propeller are called Wake Flow Devices. According to recent studies, a Wake Flow Device can eliminate cavitation and reduce fuel consumption by 5% (Leaper, 2014).

As can be seen in the figure 4.2, the red ESD reduces the amount of harmful (blue) cavitation coming from the tip of the propeller. (The red areas are high-pressure areas, the blue are low-pressure areas, and the low-pressure areas are the places where the cavitation occurs)

4.1.3 Operational Factors

The easiest way to reduce cavitation and thus reduce noise produced by the propeller, is simply to reduce speed. Studies have shown that a lower speed results in less cavitation, but under 15 knots the engine noise is the dominant factor therefore it is not the best solution (Bosschers, 2014) due to the lower thrust of the propeller. A ship owner can come up with new operational procedures, where ships have to operate at lower speeds (slow steaming). Slow steaming can have a positive effect on fuel consumption, emission and noise production. This however means that voyage time will increase, so a good consideration has to be made. A good example of this is the fact that a couple of ships has decreased their operating speed from 15.6 knots in 2007 to 13.8 knots in 2013 (Leaper, 2014)

Maintenance can also play a vital role in the reduction of noise, by maintaining a smooth and clean hull; the flow of water towards and around the propeller will be more efficient. This will result in a decrease of drag and cavitation. This can be obtained by a good maintenance schedule, and the right paint choice such as “Eco Speed”. Eco Speed is a hard paint type which can be cleaned by ROV (Remotely operated vertical) during loading and discharging (fig. 4.2.1)

Fig 4.2 ESD in situ

Fig 4.2.1 Diver cleaning the hull using a ROV
4.2 Vibrations caused by the engine room

The other main source of the harmful noise produced by vessels is caused by the engine room. The vibrations created are caused by:

- Main engine
- Generators
- Propeller shaft
- Stern tube bearings

4.2.1 The main engine

As mentioned in the previous chapter, the main engine plays a significant role in the production of vibrations. The most simple solution is to isolate the main engine from the foundation, this means that there has to be a special damper or damping material in-between the engine and the foundation. The problem by doing this is, when the main engine is isolated from the foundation it is possible that there will be some space between the engine and the foundation. This space can result in sudden movements from the engine which can cause a devastating effect on the alignment of engine, gearbox and propeller. This can result in an increase in forces on the shaft, which will produce more vibrations, noise and possibly the breaking of the shaft. A good solution must meet the following demands

- Provide good isolation between engine and foundation
- Minimal movement between engine and foundation
- Long lifespan/low maintenance

There are roughly 3 types of engines: the high rpm (more than 16 rotations per second), medium rpm (between 4 and 16 rotations per second) and the slow turning 2 stroke engines, (less than 4 rotations per second). These engines all have a different vibration frequency, this is because of the way the vibration is produced as mentioned in chapter 3.

4.2.2 Damping with rubber dampers

In order to effectively isolate the engine, the mountings must have a natural frequency of preferably half that of the engine’s generated vibration frequency. This is possible with the medium and high speed engines, due to their high frequency vibrations, but with the low speed engine, the vibrations are in the 3Hz range. The mountings need to have a natural frequency which is half of the frequency of the engine, this will mean that the mounting needs a frequency of 1.5Hz, this will result in an engine that can move too much to be considered safe. The result is that a low rpm engine is impossible to isolate using rubber dampers (Fig 4.3).
4.2.3 Alternative damping methods
As stated above the use of rubber dampers is a great way of reducing vibrations for certain engines, but for the slow speed 2 stroke the conventional way is not satisfying. A solution for this problem can be an active damping system. This system works by using actuators which can create a vibration by itself, if this vibration is the exact opposite of the engines vibration it will cancel out the vibration all together (Fig 4.4). The problem however is that in order to fully reduce the vibrations the engine will need actuators in three dimensions, which have to be activated at exactly the right time. This will create an extremely expensive and complicated system.

A more drastic, but most effective way to reduce vibrations caused by engine components, is to swap the normal diesel engine setup, with a diesel-electric setup. (van Maanen, 2000) Unfortunately this means that the conventional setup of engine/shaft/propeller has to be abandoned and vessels have to be equipped with thrusters like Azipods (fig 4.5). One of the biggest drawbacks of this conversion is that most vessels are not really suitable to convert into diesel-electric due to their design and of the lack of space. Even if the vessel is suitable, the expenses usually far exceed the benefits. It is therefore not the best way on existing vessels. It can be done on brand new vessels, the benefit of Azipods is the increase of the manoeuvrability, a side effect of Azipods due to their design is that the flow of water is uninterrupted due to the propeller in front of the drive unit design.

4.2.4 Generators
The big difference between generators and large propulsion engines is that the generator is allowed to have some movement between the generator and foundation. Therefore the isolation between the foundation and the generator can be much more effective and simpler, than with a propulsion engine. A good solution for the generator must meet the following demands:

- Long lifespan
- Provide good isolation between generator and foundation

The best way to isolate the generator is by a two-step isolator. This is a combination of two isolators stacked on top of each other, this way the vibration can be reduced to almost none. The principal of the two step isolator is that the range of vibrations that can be reduced increases due to the two different natural frequency of the isolators, and the increasing number of material transitions the vibration has to make.
4.2.5 Propeller shaft

A propeller shaft can have the following vibrations:

- Axial vibrations
- Lateral vibrations
- Torsion vibrations

The axial and the lateral vibrations can be reduced by good alignment of the shaft between engine and propeller. The major problem with the alignment of the propeller shaft is that the shaft can twist and bend when the ship is at sea. It is therefore important to consider these sudden movements and differences in height and length when aligning the shaft. Another aspect to consider is the movement caused by thermal expansion and shrinking due to fluctuating temperatures. (van Maanen, 2000)

Due to the continues changing conditions the alignment is a compromise between the best alignment and the forces that can be handled, it is therefore never the quietest solution. To compensate some of the vibrations so called "Propshaf Vibration Dampers" can be added, the basic principal of the dampers is to limit the amount of torsion created by letting individual parts of the shaft move independently form one another. This is created by placing a housing whit two friction discs that can move a little bit, in order to reduce the torsion in the shaft (Fig 4.7)
4.2.6 Stern tube bearings

The stern tube is used to support and seal the propeller shaft as it passes through the aft hull. It consists of a cast iron tube welded into the stern frame. In the old days, the shaft inside the tube was bronze coated and run against a longitudinal bearing, which, was made of narrow strips of a very hard wearing wood known as “lignum vitae.”

However nowadays, the propeller shaft has a CUNI (copper nickel alloy) liner shrunk onto it. Babbitt metal is applied over this and then machined, providing the bearing surface between the cast iron stern tube and the propeller shaft. This is lubricated and cooled by lube oil supplied from a gravity tank located under the aft peak. The propeller shaft has mechanical and/or adjustable gland seals fore and aft to prevent the ingress of oil to the sea and the aft bilge well. (bright hub engineering, 2011)

The biggest problem of this system is that the bearings are unable to absorb the vibrations, and are in direct contact with the hull. This means that the vibrations can be directly transported to the water. Most of the vibrations comes from insufficient lubrication of the bearings, this will result in bigger friction, and great shear forces. The lubricating can be improved by better alignment, additional lubrication channels or by using a different type of lubricant. It is important to remember that the temperature of the lubricant plays a vital role in the viscosity, and therefore its lubricating capabilities. To improve the lubrication the lubricant should be checked during operational temperatures, this can vary from time to time.

A specialized company should only check the alignment of the shaft, due to the difficulty and complexity of the job. It is important to check the alignment every time the shaft is disconnected for maintenance or inspection.
4.3 Isolating the ship from the water

As mentioned in the previous chapters, the basic idea of noise reduction is by isolating the noise admitting machinery. One of the more radical and innovative ideas is to isolate the entire ship from the water. The idea behind this is that it would be far more effective and cost effective than individual dampers. There are multiple ideas to obtain the desired result:

- Anechoic tile
- Bubble Curtain

4.3.1 Anechoic tile

The Anechoic tile is originally a navy product. Its use was to absorb the sound waves of active sonar, reducing and distorting the return signal, thereby reducing its effective range, and to attenuate the sounds emitted from the vessel, typically its engines, to reduce the range at which it can be detected by passive sonar. (Wikipedia, 2014) It is therefore a good solution for commercial ships as well. Some studies show a 15% decrease of the admitted noise (Wikipedia, 2014). A big problem however is that because of its navy roots, most of the technology is classified.

4.3.2 Bubble Curtain

After conducting field research, the idea of a bubble curtain arose. This literally means a curtain of bubbles which covers the whole underwater hull. The background of this experiment is that the sound wave needs to pass through several different states. First from the vessel through the water, then from the water through the air bubbles and then further on into the water. This requires energy which otherwise would be emitted through sound.

The inspiration of this subject came from drilling platforms which also use a bubble curtain to reduce the noise pollution created by the pile driving by the creating of new wind farms(fig. 4.10). The idea to implement air bubbles onboard a ship is not a new idea it is already in use for ice breakers which use a bubble curtain to reduce the resistance with the ice.

The big difference between a icebreaker and a containership is that on the containership the bubble curtain needs to be uniform along the entire side of the hull and not only the bow. This is in order to reduce the noise effectively. The possibilities and the efficiency of a curtain have never been researched, there is therefore no accurate data on the efficiency. An impression of the idea is shown in fig. 4.9 for the bottom of the hull.

![Fig. 4.9](image1.png)  ![Fig. 4.10](image2.png)
4.4 Conclusion

<table>
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<th>Efficiency</th>
<th>Sustainability</th>
<th>Feasibility</th>
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<td>Slow Steaming</td>
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</table>

++ Good

-- Bad

The question of this chapter was: “In what way can the noise be reduced?” There are a lot of ways to reduce the noise produced by vessels. As seen in the matrix above, slow steaming and diesel-electric are the best two existing solutions. A new innovative solution to this problem is a ‘bubble curtain’. This solution is the main focus of the experiment, described in the next chapter.
5. Taking the theory into practice

5.1 Introduction
As mentioned in the previous chapter (4.3.2) there is very little research on the effectiveness of the bubble curtain, although the idea is promising. Therefore a good research has to be made in the effectiveness, this chapter will describe the steps, predictions and the outcome. To get a better understanding of the effectiveness a small-scale experiment needs to be done.

5.2 The theory
The idea is a combination of two existing ideas: the bubble curtain used for reducing underwater noise while pile driving, and the idea to isolate the entire ship instead of individual components. The big question is: if these two ideas will be combined, will the noise be reduced? Based on the findings with several pile driving experiments a bubble curtain works but not under current, the big problem on a vessel is that the main point of a vessel is that it moves an is therefore influenced by a constant current. If the current can be used as an advantage of the curtain instead of being a problem that could be a big solution.

5.3 The experiment
After discussing the possibilities the idea was made to make the speed of the vessel work in our advantage, by letting it carry the bubbles along the hull. On the bottom of the hull there will be a bubble producing device just after the bow, one amidships and a last one near the stern, the bubble producing devices will stretch along the entire width of the hull to produce a continues and uniform curtain as seen in fig. 5.1.

The experiment consists of three sets of runs. In the first set of runs the noise of the pump witch creates the “current” will be measured. To establish a baseline of the ambient noise during the tests.

During the second set of runs the noise will be measured without the bubble curtain. A vibrating device will create the vibration; this will simulate the engine room noise. The cavitation will not be part of this experiment, due to insufficient simulating equipment.

Fig. 5.1 placement of the bubble producing devices

Fig. 5.2 measurement made using a decibel meter (top left corner)
During the last set of runs the principle is the same as in the second set of runs, but now with an active bubble curtain.

The noise will be measured with an underwater decibel meter, the decibel meter is situated abeam of the vessel just below the waterline as seen in fig. 5.2, the position of the decibel meter will be held at the same place during the runs, in order to get a constant measurement.

The runs will be in sets of three to minimize the risk of inaccurate measurements.

5.4 Necessary equipment
For the experiment the following equipment was needed:

- Waterproof decibel meter
- Ship model
- Simulation area
- Vibration source

The setup of the experiment is quite simple. A tank creates the simulation of the current with the pumps. The pump circulates the water from one side to the other. This creates a constant flow. In this tank the ship model is placed in a fixed place. A constant vibrating machine creates the vibration.

Setting the pump to different rotation speeds also alters the current. The location of the experiment is the engine room of the STC-building Lloydkade.

5.5 Findings
During the experiments we noticed that the ambient noise was pretty high, due to the high vibration of the pumps and the waterfall created by the moving water as can bee seen in fig 5.3. This can be seen in the baseline. The bubble curtain works perfectly under slow speeds but when the speed increases, gaps in the bubble curtain develop, and the noise increases. As can be seen in the graph, the bubble curtain loses effectiveness around the 800 RPM. The data is shown in the graph 5.1 and is shown in numbers in appendix 1.
5.3 Conclusion

After comparing the results with the theory we can conclude that the results confirm the theory, the increase in noise comparing the baseline with the bubble curtain around 800 PRM can be explained by the insufficient curtain due to insufficient air distribution. Overall the data looks promising. (The results of the experiment can be seen in graph 5.1, the data can be found in appendix 1.)

But to get a more accurate idea of its effectiveness the setup needs to be optimized to be as quiet as possible, to prevent the pollution of data.
Conclusion

The main question of this research is **How can the vessels be silenced to comply with the IMO legislation?** To answer this question we divided the research in four sub categories:

- The new IMO rules concerning noise
- The noise emitted by vessels
- Ways to reduce the noise
- Taking the theory into practice

The conclusion of the first category is that the new IMO rules consist of non-mandatory guidelines to reduce underwater noise and a universal standard has been accepted by the IMO to measure noise. Legislation with specific maximum levels of noise cannot be made yet, because of the lack of research.

It is expected that the newly built vessels have to apply to the legislation, followed by the existing fleet within a certain time. But only if the alterations to the vessels needed to be made to comply with the legislation are reasonable to execute.

The conclusion of the second category is that there are two main sources which create the noise pollution. The first source is cavitation, which is created by a different in pressure. This result in vapor bubbles that implode which creates noise. The faster the propeller rotates, the bigger the pressure different is, and the more dominant the cavitation becomes. The second source is the vibration. Most of the machinery creates vibrations. These vibrations go right through the hull and result in underwater noise. There are two types of vibrations, low frequency and high frequency. The low frequency has a higher energy level, therefore it can travel a longer distances. Cavitation and vibration are the main sources. It depends on the speed which is the biggest noise source. Above approximately the 12 knots cavitation is the biggest noise source, under the 12 knots the vibrations creates the biggest noise.

The third question was: “In what way can the noise be reduced?” . There are a lot of ways to reduce the noise produced by vessels; slow steaming, diesel-electric are the best two existing solutions. A new innovative solution to this problem is a ‘bubble curtain’.
Implementable on existing vessels | Efficiency | Sustainability | Feasibility
--- | --- | --- | ---
Bubble curtain | ++ | ++ | + | +
Anechoic tile | + | + | +/- | -
Diesel-electric propulsion | -- | ++ | + | ++
Anti-vibration mountings | ++ | +/- | ++ | ++
E.S.D. | + | +/- | ++ | +/-
Slow Steaming | ++ | ++ | +/- | ++

The fourth and final category is “Taking the theory into practice” here the focus was to look into all the possibilities that the bubble curtain had to offer. After the experiment the conclusion was that it was a viable idea, and if further researched it could be the best solution to the problem.

There are multiple answers to the main question (**How can the vessels be silenced to comply with the IMO legislation?**). Short term solutions could be slow steam areas to reduce cavitation noise. An advantage of this solution is that it is simple and it can be implemented immediately and on all vessels. Long term solutions can be the change to diesel-electric propulsion for new vessels. For all vessels the bubble curtain can be a good solution, but more research has to be conducted on this subject.
Recommendations

The experiment was performed with a vibration source inside the vessel, simulating the engine room vibrations. An idea for another experiment can be looking into the effect of the bubble curtain on noise produced by the cavitation at the propeller.

While conducting the experiment we used the facilities in the engine room at STC Rotterdam. The tub of water was close to the pumps. This resulted in extra noise. To simulate a moving vessel, water was pumped from one side to the other (as can be seen in the photos of the experiment). This resulted in a waterfall behind the vessel, producing more ambient noise. Therefore an experiment with a quieter set-up is needed.

Further research is needed for the financial effect of the bubble curtain. Will the bubble curtain effect speed? Will the curtain effect the efficiency of the propeller? What are the costs of the realization of a working bubble curtain on a vessel? These questions are important for the ship-owners, whom are paying the bills, and these questions deserve answers.
Literature list

*TUDelft.* (n.d.). Retrieved nov 10, 2014, from Cavitation on Ship Propellers:
http://ocw.tudelft.nl/courses/marine-technology/cavitation-on-ship-propellers/course-home/


Interviews

Interview RMU with Mr. de Leeuw:
What are your expectations regarding the legislation about ship produced sounds?

The circular from the MEPC will be amended. The rules will be tightened and made clear. However, I expect the circular will be a recommendation and not a compulsory circular.

How do you expect the MEPC circular will change?

I think that the IMO will put the circular in MARPOL annex VII (pollution caused by unconventional causes) as a clause/supplement. When the legislation is in MARPOL, it can be made obligatory or it will remain a recommendation, but will be made obligatory under local law.

How long do you expect it will take to make sure all vessels comply with the new law?

A final version of the legislation will not be made anytime soon. This can take ten or even fifteen years. There is still a lot of ongoing research that need to be finalized first. The results then need to be processed by the different working groups. When all of this is done, the legislation has to be written and then it has to be signed and ratified by the IMO. Even after the IMO, the legislation has to be added to local law. I expect that all of this will take a long time.

How do you think the legislation will work?

I think that ship builders and designers are the first who will encounter the new legislation. My expectation is that the IMO will make new rules for new vessels. The current fleet will follow a few years later. How many years between the new vessels and the current fleet will depend on the lifespan of specific ship parts. When the longest lifespan of a ship part will be 5 years, the time between new vessels and current fleet will be 5 years.
Interview MARIN With ir. Johan Bosschers
Firstly Mr. Bosschers started with a presentation about the Sonic project and explained a lot about this project and how far MARIN are. After the presentation Mr. Bosschers answered the remaining questions.

1. **Do all seven forms of cavitation produce the same amount of noise?**
   No. I haven’t heard of any research done concerning the levels of noise produced by the different forms of cavitation. But we do know that fleece cavitation has a bigger impact on the noise produced than tip cavitation. This depends on how fast the bubbles implode.

2. **Are all forms of cavitation equally difficult to solve?**
   Cavitation will always occur. We can increase the speed when cavitation will occur. When we increase this speed we can delay the point of where cavitation is developed. Fleece cavitation can easily be delayed. Tip cavitation is a lot harder to reduce because it occurs at the tips of the propeller. What we can do is reduce the force on the tips of the propeller. The flow of water over the propeller is not smooth. Think of waves, current etc. These irregularities cause a so called peak on the propeller tips. We can manipulate the flow over the propeller so that the peaks don’t hit the propeller at the same time. We actually measured the levels and with this method we decreased the level with 10 decibel.

3. **What are the causes of cavitation?**
   A propeller will cause cavitation because of the lower pressure behind the blade. This produces the thrust of the propeller. This lower pressure will lower the boiling point of the water. With cavitation the pressure will be so low that the water actually starts to boil. This causes little bubbles. These bubbles then implode and this implosion causes damage to the propeller and noise underwater. When the propeller spins faster, this effect will increase. The cause of unnecessary extra cavitation is the combination of the hull and the flow of water on the propeller. If the ship’s hull is poorly designed, the flow will be less smooth and the propeller less efficient.

4. **Where can we find the balance between the enlargement of the propeller, thus lowering the rotation speed and lowering the cavitation, and efficiency?**
   This doesn’t really matter. If you have a larger, slower rotating propeller, the speed at the tip will be equal to the speed of a faster rotating propeller.

5. **In an example of an empty ship, where the propeller can get above the waterline, can you reduce the cavitation simply by using ballast, so that the propeller will get below the waterline?**
   The cause of these types of cavitation are caused by the flow on the propeller. So if you ballast the ship to the optimal waterline it can help. But the main cause remains the flow of water on the propeller, not weight etc.

6. **Are there any developments concerning the flow of water on the propeller?**
   If you align the hull with the propeller you can reduce the amount of cavitation massively and increase the efficiency. The problem with aligning is the costs. It takes a lot of time and money if you want to align the hull with the propeller perfectly. Not many companies are currently willing to pay this price.

7. **To what extent is resonance a factor?**
   This will occur if the engine room resonate with the hull. This is different for every other ship.
8. Are there any other causes of noise, besides cavitation and engine room vibration?
   No.

9. We saw in a research that when a ship goes faster than 15 kts, cavitation is the main cause of noise and if a ship goes slower than 15 kts, engine room vibration is the main cause. Is this actually the same in the real world?
   During our experiments we noticed the same. The only difference is that our conclusion was that the speed was 12 kts. But this is true in the real world.

10. What are your expectations regarding the legislation about ship produced sounds?
   I think that there will be a maximum speed for different groups of ships, divided by size. When the noisiest ships are found, then those ships will get a major makeover for the long term. I know that around the United States, some of these silent areas already exist. Especially the approach areas for a port. I think that these areas will increase in size, covering a larger area.

Information gathered from the presentation and small talk:

- Largest problems caused by low frequency sounds. These sounds are hard to muffle.
- The sound levels of the underwater noise and cavitation from a US navy vessel are the core of the ISO rules, accepted by the IMO. These levels are only for deep water. Shallow water levels require more attention, because of the resonance with the seabed.
- These measurements have been made in 1/3 octave band. This is a bandwidth of an increase in frequency with a factor of $2 \frac{1}{3}$. With this form of measurement a graph can be made which gives a good impression on what frequencies the source sends out sound.
- The European Union has asked a couple of questions concerning ship produced noise:
  - The noise impact on marine life
  - Sound prediction tools and/or AIS data
  - Design and cost efficient techniques and/or solutions

We see that the EU is concerned about this subject. Especially the fact of understanding and orientation of this problem. The EU has a Good Environmental status concept for low sound producing ships. The EU wants a certificate for these vessel. This certificate comes with privileges, depending on solutions and inventions. The EU wants this certificate introduced in 2020.

- Submarines have special designed propellers, but these propellers are working under different circumstances. A submarine propeller fitted on a normal vessel will not have the desired, same effect.
- Possible solution is a bubble screen around the propeller/hull. This is already used in the offshore business with driving large poles into the seabed. (Experiment)
- Results of a research: 20% decrease in speed results in a decrease of 10 decibel.
- Vibrations of the hull are dominant. Sounds of the engine (why engineers wear headphones) can be neglected.
Notes of meeting with Mr. Klijn of Rubber Design December 18th 2014.

- Two types of sound/vibration: Construction carried sound and air carried sound
- Research ICES 209
- Sound created by the engine is not the problem. Vibrations of the engine is the main factor
- Not much research on vibrations from the ship under water. More research and more legislation on vibrations into the ship.
- Minimal engine speed 5 Hz. Higher frequency means easier ways to muffle.
- Large 2 stroke engines: Lot of power, no gearbox needed. Difficult to muffle because of low frequencies (1.5 Hz – 10 Hz).
- Medium and high speed engines are easier to muffle, cause of the higher frequencies.
- Positioning of gearbox important. In the wrong place it will effect vibration cause of forces on the gearbox from the propeller.
- 2 stroke engines hard to muffle, 4 stroke engines easy to muffle.
- Anti-vibration exists, but quite exotic and difficult to achieve with low frequency sounds.
- Anti-vibration consists of two large magnets, a lot of power. But really expensive and complex. Very difficult to fit on a ship because of the change in frequency of an engine (different power settings/rpm’s). It can be a possibility in the future, but the anti-vibration machines existing now, are only used for one single vibration can cost between the €50.000 and €100.000.
- Present technology fitted on ships: shock absorbers, rubber-metal connection.
- 100% muffle cannot be achieved.
- Cylinder ignition important, Structure Boring Noise = all vibrations created by the engine simplified to one specific frequency.
- Singlespring and doublespring (ship need a specific stiffness)
- 80%-90% level is easily obtained. Final few percentages are a lot harder. Maximum 96%-98%.
- ICES rules: Propeller needs to be perfected, diesel-electric med/high generator sets, Electric motor can be muffled with rubber shock absorbers, bow thrusters in a tunnel -> maybe a tunnel for the propeller?
- Other systems in the engine room like pumps etc can be muffled, but depends on type of pump. Furthermore, the main cause is the main engine.
- Shock absorbers have to vibrate at a lower frequency then the engine that needs to be muffled.
- Maybe isolate the whole engine room?
Appendix 1

Results Experiment.

First run
pump running

<table>
<thead>
<tr>
<th>Situation</th>
<th>Pump Speed (RPM)</th>
<th>Water speed (m/s)</th>
<th>Underwater noise (dB)</th>
<th>Underwater noise (dB)</th>
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Second run
Pump running + vibration source on

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Third run
Pump running+ vibration source on+ bubble screen on

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