Development and study of noise generation from propellers

A comparative study between different propellers

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Abstract

Noise generation from underwater activities propagates into the marine environment. For marine vessels the propulsion system generates the most noise during its operations. Naval vessels that want to operate without being detected want to control the sound generating properties of the vessel. To control the sound generating properties this project has been looking into the existing propeller of the submerged craft Carrier Seal that is produced by James Fisher Defense. Then a new and bespoke propeller has been developed with theories applied to minimize its noise generating properties. The properties of the propeller that have been altered is the number of blades, blade area ratio, pitch and skew angle. These properties have been altered with aid of the open-source software for Matlab named Openprop. From the final propeller design a prototype was later produced, tested and compared to the existing propeller of the Seal Carrier. To test and compare these two propellers a test procedure with inspiration from NATO and the Swedish Defense and Research Agency (FOI) was developed. The results from the comparison show that the sound pressure level from the propeller spectrum could be lowered with 3 dB re 1 μPa for the vessels design speed and several blade tones could be eliminated entirely. Simultaneously the efficiency of the vessel is increased throughout its speed range.

In conclusions the recommendation to JFD is to change their existing propeller to this bespoke propeller as it has proven itself to better in every way during these trials.

Keywords
Silent propellers, Propeller development, Noise generation, Skew angle, Blade Area Ratio, OpenProp, NATO STANAG no. 1136, Swedish defense and Research Agency (FOI), James Fisher Defense.
Sammanfattning


Slutsatsen som kan dras av arbetet är att JFD rekommenderas att byta deras nuvarande propeller till den förbättrade propellern eftersom den har visat sig avsevärt mycket bättre under dessa tester.

Nyckelord

Tysta propellrar, Propellerutveckling, Ljudskapande, Skevningsvinkel, Bladtäckningsarea, OpenProp, NATO STANAG no. 1136, FOI, James Fisher Defense.
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Thank you.

Anton Dunström and Fredrik Skjernov, June 2022.
Nomenclature

\((1 + k)\)  Form factor [-]

\(A\)  Transmission Loss constant [-]

\(A_{w}\)  Wetted surface area [m²]

\(c\)  Speed of sound [m/s]

\(C_F\)  Skin friction coefficient [-]

\(C_v\)  Drag coefficient [-]

d  Depth [m]

\(D_v\)  Drag [N]

d  Diameter [m]

\(I_0\)  Intensity at 1 meter [W/m²]

\(I_r\)  Intensity at \(r\) meters [W/m²]

\(l\)  Length [m]

\(M\)  Shaft moment [Nm]

\(NL\)  Background Noise level [dB re 1 \(\mu\)Pa]

\(p_0\)  Reference pressure value [1 \(\mu\)Pa]

\(p_t\)  Pressure value [\(\mu\)Pa]

\(P_{out}\)  Useful power [W]

\(P_{in}\)  Delivered power [W]

\(P_{in_{bespoken}}\)  Delivered power to bespoken propeller [W]

\(P_{in_{Existing}}\)  Delivered power to existing propeller [W]

\(r\)  Distance [m]

\(Re\)  Reynolds number [-]
NOMENCLATURE

\( s \)  Salinity [g/kg]

SE  Signal Excess [dB re 1 \( \mu \)Pa]

SL  Source Level [dB re 1 \( \mu \)Pa]

SPL  Sound Pressure Level [dB re 1 \( \mu \)Pa]

\( t \)  Temperature [\( ^{\circ}C \)]

\( T \)  Thrust [N]

TL  Transmission Loss [dB re 1 \( \mu \)Pa]

\( V_\infty \)  Free stream velocity [m/s]

\( \eta_0 \)  Propeller efficiency [-]

\( \eta_{0_{Bespoken}} \)  Propeller efficiency Bespoken propeller [-]

\( \eta_{0_{Existing}} \)  Propeller efficiency existing propeller [-]

\( \eta_H \)  Hull efficiency [-]

\( \eta_m \)  Efficiency of the engine [-]

\( \eta_p \)  Propulsive efficiency [-]

\( \eta_{seal} \)  Losses in the watertight seal [-]

\( \rho \)  Density [kg/m\(^3\)]

\( \omega \)  Angular velocity [rad/s]
# Contents

1 Introduction .................................................. 1  
1.1 Background ................................................. 3  
1.2 Purpose and Goal ........................................... 4  
1.3 Methodology ................................................ 5  
1.4 Delimitations ................................................. 5  

2 Underwater sound ............................................ 6  
2.1 Sonar ......................................................... 6  
2.1.1 Sonar equation .......................................... 6  
2.2 Hydrophones ............................................... 11  

3 Propeller design .............................................. 12  
3.1 Propeller geometry ......................................... 12  
3.1.1 Propeller reference lines ............................... 13  
3.1.2 Pitch ....................................................... 14  
3.1.3 Rake ......................................................... 15  
3.1.4 Skew ......................................................... 15  
3.1.5 Blade area ................................................ 15  
3.1.6 Ducted propellers ....................................... 16  
3.2 Propeller design ............................................. 16  
3.3 Propeller modelling ........................................ 17  
3.3.1 Underwater thrust ...................................... 17  

4 Propeller noise ................................................ 20  
4.1 Propeller blade tones ...................................... 20  
4.2 Propeller cavitation ........................................ 20  
4.3 Pressure fluctuation ....................................... 21  
4.4 Vibrations .................................................... 21  

5 Propeller design process .................................... 22  
5.1 Propeller efficiency ....................................... 22  
5.2 Propeller Sound ........................................... 23
## CONTENTS

5.2.1 Propeller blade tones ........................................ 23
5.2.2 Propeller cavitation ........................................... 23
5.2.3 Pressure fluctuation due to turbulence in wake field .... 24
5.2.4 Propeller vibrations ............................................ 24
5.3 Propeller Requirements ........................................... 25
5.4 Propeller design ................................................... 26

6 Measurement of noise ............................................. 28
6.1 NATO procedure .................................................. 28
6.2 FOI procedure ..................................................... 28
6.3 Tests methodology ................................................ 30
   6.3.1 Environmental categorization .............................. 31
6.3.2 Rig Design ....................................................... 34
6.3.3 Test protocol .................................................... 36

7 Analysis .............................................................. 37
7.1 Propeller Noise .................................................... 37
7.2 Propeller Efficiency ............................................... 38

8 Results .............................................................. 39
8.1 Position data ....................................................... 39
8.2 Transmission Loss ................................................ 41
8.3 Power spectral density .......................................... 42
8.4 Broadband ........................................................ 44
8.5 Background sound ............................................... 44
8.6 Propeller Efficiency .............................................. 45
8.7 Errors .............................................................. 45

9 Discussion .......................................................... 46
9.1 Propeller design process ...................................... 46
9.2 Resulting Noise Generation .................................... 47
9.3 Propeller efficiency ............................................. 48

10 Conclusion ........................................................ 50
10.1 Future Work ..................................................... 50

References ............................................................ 51

A Test protocol
   A.1 Test 1 (240422) ............................................... 
   A.2 Test 2 (010622) ................................................ 

ix
# List of Figures

1.0.1 JFDs 8-man swimmer delivery vehicle in semi-submerged mode [14] . 2
1.0.2 Picture of electrical thrusters when the Carrier is in surface mode [picture by authors]. ................................................. 2
1.1.1 Different frequencies where noise is typically observed for marine vessels [12] ................................................................. 4

2.1.1 Illustration of the parameters included in the sonar equation for a passive sonar [17] [modified]. ........................................... 7
2.1.2 Illustration of geometrical spreading from a source [28]. ........... 8
2.1.3 Refraction of sound during different times of the year [17] (modified). 9
2.1.4 Salinity measurements in per mille made by Naturvårdssverket in the Baltic sea [21]. ................................................................. 10

3.1.1 Reference system used for the propeller, from ITTC in 1968 [5] .... 13
3.1.2 Reference lines that aids in the description of the individual propeller blade [5]. ................................................................. 13
3.1.3 Pitch definition described as: a) on a cylinder with radius $r$ and b) . 14
3.1.4 Definition of propeller skew [5]. ............................................. 15

5.2.1 Illustration of trailing edges along the trailing edge of the suction side of the blade [3]. ................................................................. 25
5.4.1 3D rendering of new propeller. ............................................. 27
5.4.2 The existing and bespoken propeller put next to each other. Illustrating how the geometries has been changed. ......................... 27

6.2.1 Track setup for the initial FOI test procedure [27]. .................... 29
6.2.2 Illustration of different test rigs, either as autonomous (a) or surface connected (b) [27]. ......................................................... 30
6.2.3 Description of the track and the vessels relation to the hydrophone [27]. 30
6.3.1 Test track design. ................................................................. 31
6.3.2 Potential test cite locations. ................................................. 32
6.3.3 Camera and flashlight mounted on a rope that is used for sediment investigation. ........................................... 33
6.3.4 Results from sediment investigation. ................................. 33
6.3.5 Test rig for H1 with specification of the parts included. ............. 34
6.3.6 Test rig for H2 with specification of the parts included. ............. 35

8.1.1 Trajectories for two different test runs with the drift resulting in the jump presented at the end of the run. .......................... 40
8.1.2 Trajectories for two different test runs with the deviation from the desired course resulting in no clear CPA for the bad run. ......... 40
8.1.3 Trajectories when the position readings shows an irregular pattern and the bearing used to correct for it. ................................. 41
8.2.1 Figure showing the broad band amplitude over the logarithmic distance from the source. Meaning that the amplitude at \( \log(r) = 0 \) represents the source level. (Not actual amplitude values) ......................... 41
8.3.1 PSD plot showing the frequency content of the broadband signal from the carrier seal propelled at 3 knots. (Not actual amplitude values) .... 42
8.3.2 PSD plot showing the frequency content of the broadband signal from the carrier seal propelled at 4 knots. (Not actual amplitude values) .... 43
8.3.3 PSD plot showing the frequency content of the broadband signal from the carrier seal propelled at 5 knots. (Not actual amplitude values) .... 43
List of Tables

2.1.1 Typical sources of noise in the water [17].......................... 11
2.2.1 Weight and calibration data provided from Ocean Instruments [22–24]. 11

5.3.1 The interval of the required thrust when using the method presented in chapter 3, calculated with equation 3.6 and 3.10. ..................... 26
5.4.1 Changes made to the existing propeller to make it more efficient and to produce less noise. ........................................ 27

8.4.1 Showing the change in source level between existing and bespoke propeller for different speeds and frequency regions .................. 44
8.5.1 Showing how the distances at when the Carrier is barely detectable (SE=0) decreased for the different speeds. .......................... 44
8.6.1 Showing the efficiency improvement from the existing to bespoke propeller for different speeds ....................................... 45
Chapter 1

Introduction

In general, underwater activities generates underwater noise that propagates out into the marine environment. For ships it is predominantly the propulsion that generates noise, especially at higher speeds where the propeller cavitates. However, the major issue with propulsion for ship owners is to be fuel efficient rather than silent. The awareness has increased on the negative effects of noise, resulting in an interest from the shipping industry to combine fuel efficiency with low-noise emission. For Naval ships fuel efficiency is not a prime target, instead low signatures (silent operation) is. A capability of particular relevance for submarines. The dominating noise source of all vessels is the propulsion system and especially the propeller itself [6]. To achieve both low sound levels and high fuel efficiency is challenging and a trade off has often to be made. In this study a Naval vessel supplied by James Fisher Defence Sweden AB (JFD) was employed to study noise levels in different speed registers. The vessel has three different modes of operations. Firstly a surface mode where it has a diesel engine running a water jet with a maximum speed of 30 knots. Secondly there is a semi-submerged mode where it is driven with either the diesel engine or electric thrusters. Lastly it can be operated in a submerged mode with a maximum operating depth at 40 meters and at a speed of 5 knots from the electric thrusters. JFD’s interest is to assure that the vehicle is as stealth as possible when operating submerged. This study was thus focused on the sound emitted from the propellers that can reveal its submerged presence when passing surveillance system. For this particular project the 8-man swimmer delivery vehicle Carrier Seal presented in figure 1.0.1 [15] was used to determine the sound levels. The vessel will be further referred to as Carrier.
In this project sound generation of the electric thruster was studied. For this purpose a bespoke propeller was designed with the aim that the level of the sound generated compared to the "normal" propeller should be lower. This opened up for a comparative study between the existing and the bespoke propeller. For this comparison tests were performed from which the sound performance were gathered and compared between the existing propeller shown on figure 1.0.2 and the bespoke propeller.

The development of marine propulsion has been ongoing since the 17th century. At the time propeller development followed different tracks taking inspiration from windmills, e.g Archimedes screw or paddles [8]. By the end of the 19th century propeller propulsion as we know it today emerged as the standard practice and the future development has been focused on cavitation control and increased efficiency [8].
Today many different technologies are used for marine propulsion. There exist a wide range of propellers that can be used, fixed pitch propellers have been the most commonly used propeller throughout history [7]. The fixed pitch propeller is simple to produce and run with a high efficiency in the operation condition it was designed for. Today the use of controllable pitch propeller have gained attraction in the ship industry as you gain the ability to retain a high efficiency in different operating conditions, the draw back is the increasing complexity of the propeller that lead to reduced the reliability. Both fixed- and controllable pitch propellers can be used in different configurations. They can be used in contra-rotating propeller setups to take advantage of the rotational energy of the slip stream from the propeller in front, but the design comes with a lot of mechanical challenges [7]. A concept that has been proven to yield design advantages to the propeller is to mount it in a duct as seen in figure 1.0.2. The duct can be used to control the inflow to the propeller, the concept is almost exclusively used in slow speed applications to increase the efficiency. At high speeds the duct can have an negative effect on the overall propulsive efficiency [7].

Other technologies that are being used today is water jet propulsion. The water jet accelerate water through a pump that is expelled aft of the ship and accelerate the craft. This type of propulsion have mostly been used in smaller craft.

1.1 Background

For military applications it is desirable to avoid detection no matter if it is in the air, on land/water or underneath the surface. The development and knowledge about sound propagation under water started of during the first world war and continued through the second world war and the cold war. A major break through was made in the 60s with the digital signal processing [17]. When it comes to transmitting energy in water, sound is by far the most efficient phenomenon. Other types of energy has a very limited range where as sound can travel for thousands of kilometers under the right circumstances [17]. It is hydro acoustic energy that is transmitted through water particles. It can be illustrated by a membrane that is held under water and caused to vibrate. The vibration of the membrane is transmitted to the water particles and if a second membrane would be placed in the water, it would start to vibrate excited by the transmitted energy [17]. The technique to utilize acoustic signals in water is known as SONAR that originates as an acronym for SOund NAvigation and Ranging [13].

Because of the favorable acoustic properties it is highly desirable to minimize the emitted sound from military vessel. For clarification, sound emitted from the vessel will be referred to as noise. Thus meaning that noise from the vessel is desirable to identify and to minimize. Sound that already exists in the water produced by animals, waves, wind and other boats, will be referred to as sound.
The noise emitted from a vessel are generated by several different sources for example the engine, auxiliary machines or other ship activities. In figure 1.1.1 different noise sources are shown and noteworthy is that several of them originates from the propulsion [12]. When a propeller is rotating under water acoustic waves are produced. These waves are radiated out into the marine environment and as a result can be detected. The noise from a propeller can be categorized related to the frequencies it is radiating [12]. Figure 1.1.1 shows frequencies where the different noise sources are normally found. The spectral characteristics of the noise differs between the different sources, the propeller blade tones are appearing as a few discrete tones, whilst the cavitation noise is a broad band signal covering a large span of frequencies [12].

Figure 1.1.1: Different frequencies where noise is typically observed for marine vessels [12]

The most dominant noise sources of underwater propellers are: propeller blade tones, propeller cavitation, pressure fluctuation due to turbulence in the wake field and propeller vibrations. The relative intensity of these sources are dependent on the propeller design. With this in mind, the emitted noise can be altered by innovative design.

1.2 Purpose and Goal

The purpose of the study was to reduce the noise of the propulsion when the carrier was submerged. To achieve this two goals were set. Firstly, to design a new ”silent” propeller with low-noise characteristics. Secondly, to perform in situ measurement of
underwater noise both from the ordinary propeller and from a silent propeller. The ordinary propeller of the carrier will further be referred to as the existing propeller and the new "silent" propeller will be referred to as the bespoke propeller. From the comparative study of the two propellers, conclusions can be drawn concerning what aspects of propeller design that affects the emitted noise. A comparison in regards of efficiency can also be done since the fuel efficiency and low-noise might be contradicting requirements.

This project characterized the signature of the vessel with a focus on the acoustic signature, which was directly related to the two propellers. The design of the silent propeller is a challenging task and due to time restrictions was done based on best practice and theoretical aspects.

1.3 Methodology

In this project there were two methods used. One being a theoretical method applied to the propeller design were literature on the subject was studied and applied to the design. The second method used was experiments were the Carrier was used to conduct field tests of both the existent and bespoke propeller. The results from the in situ measurements were used to evaluate the results based on theoretical aspects.

1.4 Delimitations

The project is delimited to study of noise emitted from the propeller other sources of noise were identified but not investigated. The flow adjacent to the hull crucial for presetting of the water entering the propeller was not an object for the analysis, because of that the placement of the thruster was not included in the analysis. The integrity of the hull remained intact during the study and for that reason was the outer dimensions of the bespoke propeller unaltered even though an increased diameter could have been beneficial.
Chapter 2

Underwater sound

Hydrophones are sensors designed to be sensitive to sound in water. [17]. Several hydrophones can be used in a sonar system to detect the presence of acoustic signals but also the determine the source bearing [26]. The following section will present the method that was used to analyze the measured acoustic signals.

2.1 Sonar

The basic function of a sonar system is to detect acoustic energy [13]. There are mainly two types of sonars, active and passive. The active sonar system is emitting acoustic energy and subsequently detects the acoustic energy that is returned back to the system and thereby can identify a target [13]. For a passive sonar system the acoustic energy is only received by the sonar without any prior transmission of energy. This technology relies on the premise that the source itself emits sound that can be detected [17]. In this study passive sonars were used to measure the signature of the Carrier.

2.1.1 Sonar equation

The units used for the sound level is expressed in decibel (dB) and is named as the Sound Pressure Level (SPL). Decibel is defined as a relationship between the pressure \( p_1 \) and a reference value. For underwater acoustics the reference value is given as \( p_0 = 1 \mu Pa \). The expression for the sound pressure level is shown in equation 2.1 [17]. It is noteworthy that dB is a logarithmic expression, yielding that a doubling of sound pressure results in an increase of 6dB.

\[
SPL = 20 \log \left( \frac{p_1}{p_0} \right).
\]  

(2.1)
The sonar equation describes the relation between different physical phenomena. Terms used in the equation for a passive sonar is given by equation 2.2.

\[ SE = SL - TL - NL \]  

(2.2)

As pointed out previously the sonar equation is describing the relation between different physical phenomena. On the left side of equation 2.2 the signal excess (SE), which is the amount of \( dB \) the signal is above natural ambient sound. SE is defined as the excess of signal that the sonar detects, illustrated in figure 2.1.1. When \( SE = 0 \) \( dB \) the source is undetectable [17] since the noise emitted from the source cannot be distinguished from already existing sound.

![Diagram of sonar equation parameters](image)

Figure 2.1.1: Illustration of the parameters included in the sonar equation for a passive sonar [17] [modified].

The first term on the right side of equation 2.2 is the source level (SL). For a passive sonar and the Carrier case this is the radiated noise from the vessel consisting of the following sources; mechanical, propeller, hydrodynamic and transient noise [17]. The mechanical noise stems from mechanical vibrations in the hull that are radiated into the water. What typically causes this kind of noise is unbalanced rotating parts and mechanical pumps used to maintain course and depth [17]. Propeller noise is radiated by the propeller motion in the water. The noise is proportional to the propellers rotation and the number of propeller blades [17]. Other types of propeller noise is propeller singing, propeller noise due to unbalance and noise caused by cavitation [3, 6]. A more thorough descriptions of noise related to propellers are given in chapter 4. Other types of noise that is part of SL is transient noise, which are sounds related to the activity on board the vessel that can occur from pumps or other impulsive events.
that occurs as the result of vessels operation [17]. SL is given from equation 2.1 and by
definition \( p_1 \) = sound pressure level one meter from the source [17].

The second term on the right side of equation 2.2 is the transmission loss (TL). TL
describes the effect of attenuation of the wave, which includes geometrical spreading,
absorption and anomalies. Geometrical spreading describes the decrease of the sound
level with the distance from the source [28]. Initially the sound propagates spherically
out from the source, when the wave front reaches the sea surface and the seabed it
starts to propagate in a cylindrical mode [28]. This phenomenon is illustrated in figure
2.1.2.

![Illustration of geometrical spreading from a source][2]

Figure 2.1.2: Illustration of geometrical spreading from a source [28].

TL is expressed with regards of the sound intensity in the following way:

\[
TL = 10 \log \frac{I_0}{I_r}. \tag{2.3}
\]

Since \( SL = 10 \log (I_0) \) at a distance of 1 meter and \( I_r \) equals the intensity at a distance \( r \)
[17] the geometrical losses can be expressed as:

\[
TL_{Geometrical} = \begin{cases} 
Spherical, & 20 \log(r) \\
Cylindrical, & 10 \log(r) 
\end{cases} \tag{2.4}
\]

where \( r \) is the distance from the source to a point \( r \) [17]. The actual spreading is often
somewhere between spherical and cylindrical and thus the constant is between 10 and 20, yielding equation 2.5 as an expression for TL. The Swedish Defense Research
Agency (in Swedish, FOI) have found that \( A = 17 \) is a good estimate for shallow waters
of the Baltic sea for frequencies radiated by ships [27]. This means that the value \( A \) is
directly related to the location of the tests and can be referred to as an experimental
transmission loss, see expression 2.5:
\[ TL_{Experimental} = A \log(r) \] (2.5)

The second phenomena when considering TL is absorption that occurs when energy is lost due to friction between the water particles that results in heating. The energy losses related to absorption is increasing with increased frequency. Properties of the medium such as salinity and temperature of the water has an influence. The effects of absorption is in the range of \(0.15 - 1 \text{ dB/km}\) for the Baltic sea for frequencies between 5-20 kHz [17]. In case of frequencies below 10 kHz and at ranges below 10 km the effect of attenuation can be neglected.

The third phenomenon is transmission loss caused by anomalies. It could have several causes but two of them are reflection and refraction. During summer refraction has to be regarded due to a strongly changing sound speed profile caused by heating of the upper layer of the sea [17]. Refraction is caused by water layers with different temperature. The temperature gradient is greater during summer when the water on the surface is warmer than the water below and the effects is that the wave front of radiated noise is refracted down towards the seabed. In figure is 2.1.3 the sound speed profiles shown for both summer and winter scenarios [17]. Reflection on the other hand is typically caused by hard objects on the seabed or inside the sediment that reflects the sound [17].

![Image of sound speed profiles for summer and winter](image)

Figure 2.1.3: Refraction of sound during different times of the year [17] (modified).

In the early spring the temperature of the water is fairly constant throughout the water column, yielding a constant speed profile (isoveli) [17]. The speed of sound in water is dependent on temperature, salinity and depth. The relation between these and the sound speed was given empirically by Medvin that found it to be: [17].
\[ c = 1449,2 + 4,6t - 0,055t^2 + 0,00029t^3 + (1,34 - 0,01t)(s - 35) + 0,016de \] (2.6)

where \( c \) is the speed of sound in meter per second, \( t \) is the temperature in Celsius, \( s \) is the salinity in per mille and \( de \) is the depth in meter. The Baltic sea is brackish and the salinity varies and is highest at the entrances of the Baltic Sea and then drops further north. Figure 2.1.4 illustrates the different levels of salinity in the Baltic sea. In Stockholm the salinity is measured to be 5 per mille.

![Figure 2.1.4: Salinity measurements in per mille made by Naturvårdsverket in the Baltic sea [21].](image)

The main attenuation is expected to be geometrical loss, but it can be assumed that reflection and refraction will play a role, especially the sediment will affect the reflection of sound.

The third and last term in equation 2.2 is the noise level (NL). It is defined as the
ambient sound all but the noise that the carrier was emitting. Typical sources of NL is other vessels, wind, waves and currents. In table 2.1.1 the typical sources of noise and their respective frequency and sound level are listed.

Table 2.1.1: Typical sources of noise in the water [17].

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>Source</th>
<th>NL [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 20</td>
<td>Currents</td>
<td>80 - 110</td>
</tr>
<tr>
<td>20 - 200</td>
<td>Vessel traffic</td>
<td>60 - 70</td>
</tr>
<tr>
<td>500 - 50 000</td>
<td>Wind and waves</td>
<td>30 - 60</td>
</tr>
</tbody>
</table>

In conclusion, for the field trials on the carrier the absorption can be neglected since the distances were relative short. In spring when the measurement was conducted the temperature was constant throughout the water column and isoveli can be assumed valid. With these assumption the TL reduces to equation 2.5. Thus to estimate the source level (SL) the constant A has to be determined.

2.2 Hydrophones

Two different hydrophones were used to collect data during the field work. The manufacturer of the hydrophones was Ocean Instruments from New Zealand. The two different models used were, Sound Trap 300 and Sound Trap 500 from Ocean instruments both will be referred to as ST300 and ST500 in this report. Both ST300 and ST500 use internal batteries and storage and is therefore 100% autonomous when deployed in the water [23, 24]. In addition to sound recordings the ST300 is equipped with an auxiliary temperature sensors that record the water temperature simultaneously with the sound recording [23, 24]. Information such as weight in water and calibration data is provided from the manufacturer and is presented in table 2.2.1.

Table 2.2.1: Weight and calibration data provided from Ocean Instruments [22–24].

<table>
<thead>
<tr>
<th>Model</th>
<th>ST300</th>
<th>ST500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>0.5 kg</td>
<td>1.5 kg</td>
</tr>
<tr>
<td>Calibration</td>
<td>176.5 dB rel $1 \mu$Pa</td>
<td>177.4 dB rel $1 \mu$Pa</td>
</tr>
</tbody>
</table>
Chapter 3

Propeller design

For the design process of the propeller there are several aspects in the design that needs to be accounted for. In this chapter the aspects of propeller design will be discussed, starting with aspects of propeller geometry followed by physical phenomena and finally a description of the design process of the propeller.

3.1 Propeller geometry

Propeller geometry are described in different ways. There is no standard on how to do it. In this report the reference system from the International Towing Tank Conference (ITTC) in 1968 was used [5]. The ITTC used a global Cartesian system shown in figure 3.1.1 with the X-axis pointing forward and the Y-axis pointing in the starboard direction and the Z-axis pointing downwards. It is convenient to employ a local reference system as shown in figure 3.1.1. The two x-axes coinciding with each other and the yz-plane rotating with the angle \( \phi \) in relation to the fixed coordinate system[5]. A point in the local coordinate system was described by Carlton (2017) by the following relations:

\[
\begin{align*}
  x &= f(\phi) \\
  y &= r \sin(\phi) \\
  z &= r \cos(\phi)
\end{align*}
\]

(3.1)
CHAPTER 3. PROPELLER DESIGN

![Diagram of propeller reference system]

Figure 3.1.1: Reference system used for the propeller, from ITTC in 1968 [5]

### 3.1.1 Propeller reference lines

When describing a propeller and its dimension, the references system and the geometry of the propeller needs to be related to each other. The reference line described in figure 3.1.2 is oriented in the direction as the z-axis in the local coordinate system in figure 3.1.1.

![Diagram of propeller reference lines]

Figure 3.1.2: Reference lines that aids in the description of the individual propeller blade [5].

The Generator line in figure 3.1.2 is defined by the intersection of the cylindrical coordinate between the leading and trailing edges of the propeller propeller blade and the plane defined by the propeller reference line and the x-axis [5]. As seen in figure 3.1.2 the generator line is defined from the root to the tip of the blade [5].

13
3.1.2 Pitch

Pitch or the inclination of the propeller blade can be defined as a the rotation of a point P on the propeller blade, which rotated $\phi = 360^\circ$ moves the propeller a distance $P$ forward, as shown in figure 3.1.3. In descriptions of propellers this distance is often presented in inches, similarly as the diameter of the propeller [5]. Pitch is also described by the pitch angle $\theta$ as illustrated in figure 3.1.3 and following [5] expressed as:

$$\theta = \tan^{-1}\left(\frac{P}{2\pi r}\right).$$

Figure 3.1.3: Pitch definition described as: a) on a cylinder with radius $r$ and b)

The pitch angle can be either constant along the blade or distributed along the length of the blade yielding a twisted blade. For a twisted blade the pitch is commonly described as a mean pitch angle $\theta_{mean}$ at 60-70% of the propeller radius [5, 16].
3.1.3 Rake

Similarly to pitch, rake can be described both as a distance and as an angle. When using distance, rake is defined as the distance AB in figure 3.1.2 at the propeller tip in the xz-plane. The rake angle is instead defined by the inclination between the generator line and the propeller reference line also shown in figure 3.1.2 and following [5] given by the following expression:

\[ \theta_{rake} = \tan^{-1} \left( \frac{AB(r/R = 1)}{R} \right) \tag{3.3} \]

3.1.4 Skew

Skew is described in the yz-plane in figure 3.1.1. Along the propeller blade skew is defined as the angle \( \theta_{s}(x) \) between the blade reference and the propeller reference line for each radial segment of the propeller blade [5]. In figure 3.1.4 both the skew angle of each propeller segment is defined. The angle \( \theta_{s}(x) \) is considered negative for angles forward of the blade reference line. The overall skew however is defined as the largest angle drawn from the center line of the propeller as a tangent to the blade reference line and the propeller tip, shown in figure 3.1.4.

![Figure 3.1.4: Definition of propeller skew [5].](image)

3.1.5 Blade area

The size of the blades can be designed to vary in many different ways. In propeller design, the area of the propeller blades is considered in different ways [5]. Being either projected, swept, expanded or swept. These different representations yields slightly different results and its worth noticing when considering propeller development. For
this project the blade area representation will be the expanded area $A_E$. Because it is
the most simple area to calculate it is widely used for propeller design purposes. The
expanded area is given by the following expression:

$$A_E = Z \int_{r_{hub}}^{R} c \, dr$$

(3.4)

where $Z$ is the number of blades and $c$ being the length of the chord. Because of this
$A_E$ is not actually a geometrical representation of the blade. It is instead expressed
by the chord length for the respective radial segment [5]. The blade area ratio (BAR)
yields a relationship between the propeller disc area and the area of the actual propeller
following [5] expressed as:

$$BAR = \frac{4A_E}{\pi D^2}$$

(3.5)

3.1.6 Ducted propellers

To increase performance of a propeller ducts can be used. Ducts are often symmetric
around the shaft center line with an airfoil cross section. The duct is mainly used
when the propeller is under heavy load and in slow speed applications. The ducts
main purpose is to increase the efficiency of the propeller by changing the inflow to
the propeller and reduce bottom suction in shallow waters, the duct also protects the
propeller from damage. There are mainly two types of ducts that are being used today,
accelerating ducts and decelerating ducts [7].

3.2 Propeller design

When designing a propeller there are some physical phenomena that need to be dealt
with. One of the biggest challenges in the propeller industry is cavitation[7]. A
simplified description of cavitation is that it occurs when the static pressure in the
liquid is below the vapor pressure. When this happens vapor-cavities are created on
the propeller surface, and when the pressure around the cavities grow they implode
which send shock waves that radiate noise as well as cause damage to the propeller
surface[4].

The vapor pressure of water is dependent on numerous things. With a rising
temperature of the water the vapor pressure becomes considerably larger. Thus,
cavitation is less of a problem in cold water. Another factor affecting vapor pressure
is the salinity. With a high salinity the vapor pressure goes down which suppresses
cavitation [4].
In this description the inception of cavitation occurs when the pressure of the liquid is below the vapor pressure. However, in reality there are other factors, for example the liquids ability to resist tension, or the gas content in the liquid that affects the cavitation. Cavitation is a complex phenomenon that is difficult describe. A simplified model is a great start to get an understanding of the conditions results in propeller cavitation [4].

### 3.3 Propeller modelling

When designing propellers the open-source program OpenProp was used that is written for use with Matlab. It is used for the purpose of designing and analyzing different propeller designs. In the end it can be used to produce an optimized propeller that fulfills the specified conditions [11]. The theory applied in the numerical model is *moderately-loaded lifting line theory*. In this theory the propeller blades are represented by radially varying bound vorticities [10]. The propeller blades are modeled as two dimensional discrete sections with two dimensional properties at different radius while the three dimensional loads on the blade are determined by integration of these sections over extent of the blade [11].

The numerical model has to be adapted to the design and specifications of the vehicle, e.g. thrust, design speed and RPM [11]. There are a set of input parameters related to the geometry of the propeller, such as number of blades, propeller diameter, chord distribution, skew angle and if the propeller should be ducted [11]. The OpenProp model determines the pitch distribution that is needed to meet the required thrust and design speed with the set propeller criteria. An estimated efficiency of the propeller is also calculated. Optionally, theoretical values for cavitation is also calculated.

#### 3.3.1 Underwater thrust

In propeller design the thrust is an important design parameter. It directly affects the propeller geometry. When the propeller is operating in the desired operating condition it is important that it delivers enough thrust to propel the craft in the desired velocity. Therefore one design input to the propeller was the required thrust. The required thrust was estimated with data from the Carrier. To get a more precise estimations two different methods were used to estimate the required thrust. Those two methods was firstly to estimate the drag of the vessel when it was operated under water and then secondly to estimate the efficiencies of the Carrier. From those two methods an interval of the required thrust was estimated.
Estimating drag

To propel the craft the drag force has to be overcome. To estimate the required thrust of the propellers, the drag of the entire craft was calculated. To calculate the drag the craft was simplified to have the shape of a torpedo[25]. The total drag \( (D_v) \) of an torpedo shaped hull can be calculated according to equation 3.6

\[
D_v = \frac{1}{2} \rho A_w C_v V_\infty^2. \tag{3.6}
\]

Where \( A_w \) is the total wetted surface area, \( C_v \) is the drag coefficient and \( V_\infty \) is the free stream velocity around the craft. The viscous effects of an underwater craft consists of two components, skin friction and body drag [25]. These effects contribute to the drag coefficient in equation 3.6. The skin friction is due to the viscose shear in the water flowing near the hull. The skin friction coefficient can be estimated as a function of Reynolds number according to the ITTC 57 correlation line and is given by

\[
C_F = \frac{0.075}{(\log(Re) - 2)^2} \tag{3.7}
\]

Where \( C_F \) is the skin friction coefficient and \( Re \) is Reynolds number. The body drag or pressure drag is due to different pressure distribution in the aft and stern of the craft. The pressure drag is represented by a form factor applied to the friction coefficient[25]. This form factor can be calculated according to

\[
(1 + k) = 1 + 1.5(d/l)^{3/2} + 7(d/l)^3 \tag{3.8}
\]

where \( k \) is representing the added resistance due to form drag, \( l \) is the length and \( d \) is the diameter of the underwater craft. The total drag coefficient from viscous effects can therefore be calculated according to

\[
C_v = (1 + k)C_F \tag{3.9}
\]

where \( C_v \) is the drag coefficient due to viscous effects, \( C_F \) is the friction coefficient and \( (1 + k) \) is the form factor that is representing the added resistance due to pressure drag. When the design speed is know together with the dimensions of the craft the total drag can then be calculated with equations 3.6-3.9. The drag is used as a lower estimate of the thrust that the propeller need to produce to overcome the drag forces.
Estimating efficiencies

The second method to determine the required thrust ($T$) is to estimate the efficiency of the craft and use data on power provided by the engine ($P_{in}$) and vehicle speed to determine the thrust that the propeller was delivering. If the speed and engine output is known the thrust can be calculated according to

$$T = \frac{P_{in} \eta_p}{V_{\infty}}$$

(3.10)

where $T$ is the thrust from the propeller, $P_{in}$ is the delivered power from the engine to the propeller shaft, $V_{\infty}$ is the free stream velocity and $\eta_p$ is the total propulsive efficiency[16] and can be subdivided into a products of efficiencies

$$\eta_p = \eta_H \eta_{seal} \eta_m \eta_0$$

(3.11)

where $\eta_H$ is hull efficiency, $\eta_{seal}$ is losses in the watertight seal between motor and propeller, $\eta_m$ is the efficiency of the engine and $\eta_0$ is the propeller efficiency.

Estimating the efficiencies of the Carrier using engine and speed data from field tests, the required thrust can be calculated by employing equation 3.10 [16].
Chapter 4

Propeller noise

Emitted noise from the propeller that is transmitted into the water originates from different physical phenomena related to the propeller and its movement in the water. In the following chapter, these phenomena and effect that cause the emitted noise will be discussed.

4.1 Propeller blade tones

The propeller blade tones are often caused by the displacement of water and by the difference of pressure between the pressure side and suction side of the blades [6]. The frequencies are predictable and appears as a few discrete frequencies. They depend on the rotation speed and the number of blades of the propeller. To reduce the sound at these frequency the most important factor is the rotation speed[2]. To allow for a reduced speed of the propeller, the propeller torque needs to increase at a lower propeller speed. This can be done in a different ways. Adding blades to the propeller give more torque per rotation. Alternatively increasing the pitch will give the same effect.

4.2 Propeller cavitation

The absolute biggest contributor to noise on a propeller is cavitation [6]. When designing a silent propeller it is imperative that there is no cavitation. The noise of the cavitation is spread over a broad band of frequencies, with a random sound signal behavior [4]. A simplified explanation of cavitation is that it occurs when the static pressure in the liquid is below the vapor pressure. When this happens vapor-cavities is cratered on the propeller surface, when the pressure around the cavities grow they implode which send shock waves that radiate noise. There are many types of cavitation such as tip cavitation or hub cavitation. To reduce the risk of cavitation the pressure
CHAPTER 4. PROPELLER NOISE

differences has to be reduced as well as making the pressure distribution even over the blade.

To minimize cavitation and make the pressure more evenly spread there are some aspects to consider when designing a propeller. First the propeller speed can be reduced to decrease the pressure difference that the propeller is causing[2]. Another way of making the pressure more evenly spread out is by changing the geometry of the blades to expose the areas where cavitation is likely to occur. At the tip the blade speed is the highest, this makes the tip cavitation being the first type of cavitation the blade experience in most cases. By introducing a variable pitch that has a lower pitch at the tip it is possible to decrease this pressure difference on the tip of the blade [4]. It is also possible to introduce a large skew angle that spreads out the pressure more evenly [20].

4.3 Pressure fluctuation

The pressure fluctuation in the wake field make the pressure distribution fluctuate on the propeller blades [9]. This is an uncontrollable effect that is difficult to address since it depends on several factors. To deal with this effect the flow can be made less turbulent around the propellers by changing the hull structure or adding a duct. It is also beneficial to reduce the fluctuation from the propeller itself by adding more blades to the propeller to make each blade carry less load. Another way of lowering the pressure fluctuations from the propeller is to add a large skew angle[20].

4.4 Vibrations

When the propeller vibrates it causes noise. To prevent vibration it is imperative to have a well balanced propeller [3]. Propeller vibration can be reduced by adding more blades or by employing a larger skew angle. When the natural frequency of the propeller matches the vibration the propeller edge starts singing. The singing can be prevented by adding a anti singing edge in the trailing edge of the blades [2].
Chapter 5

Propeller design process

The goal with the propeller design is to design a silent propeller with a high efficiency. A silent propeller has different design characteristics than an efficient propeller. Therefore the design needs to be a compromise between the two design goals, but at the same time comply with the requirements and limitations off the existing craft.

5.1 Propeller efficiency

The propeller efficiency is the ratio between the thrust of the propeller and the total power that the engine is producing to rotate the propeller. The power can be estimated as a product between the shaft torque $M$ and the angular velocity $\omega$ [16]. This is the total power that the engine is producing to cause the propeller to rotate. Useful power (power used to move the vehicle) that the propeller is creating can be estimated using the product between the inflow velocity at the propeller $v_A$ and the propulsive torque created by the propeller $T$[16]. With this in mind the propeller efficiency $\eta_0$ in open water can be estimated according to

$$\eta_0 = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{V_\infty T}{\omega M} \quad (5.1)$$

where $V_\infty$ is the free stream velocity, $T$ is the thrust force, $\omega$ is the angular velocity of the propeller and $M$ is the shaft momentum [16]. The propeller efficiency is depends on different factors. One major factor is the ratio between shaft torque $M$ and propulsive torque that the propeller is creating. This relation depends on the geometry of the propeller. The most prominent geometric characteristics that effect the ratio between supplied torque and useful torque is pitch and diameter [16]. To strictly increase the efficiency the pitch should be as low as possible. This condition often comes in direct conflict with other factors such as the required torque at a certain angular velocity and
ship speed. Another factor that decreases the efficiency is the blade area ratio. The efficiency decrease with an increased blade area ratio. The blade area should be as low as possible but the actual size is limited by other aspects of the design.

The angular velocity is one of the major factors to the propeller efficiency. Low angular velocity yields high efficiency. This in direct conflict with the pitch angle because the propeller has a required torque that needs to be produced to propel the craft at the design speed. A lower angular velocity infer an increased pitch angle, which results in lower ratio between useful and delivered torque. Because the angular velocity has a bigger effect on the propeller efficiency it is more beneficial to increase pitch to make room for an increased angular velocity.

It follows, by lowering of angular velocity that the torque produced per rotation of the propeller must increase. As written above the simplest solution is to increase the pitch. Alternative tuning is to increase the torque from the propeller by the addition of blades, which will create more thrust during one turn. The addition of blades is often considered to decrease the overall efficiency even with the benefit of the lowered angular velocity[5]. But because the lowering of angular velocity have beneficial consequences on the emitted noise, submarine propellers often have many blades to allow for a low angular velocity.

5.2 Propeller Sound

In the design of a silent propeller the main objective is to limit the emitted noise of the propeller, as described previously in chapter 4.

5.2.1 Propeller blade tones

To limit the propeller blade tones the optimal design is to decrease the angular velocity of the propeller. This is in line with the efficiency of the propeller. And the geometry characteristic of a slow spinning propeller is that of a high pitch propeller with multiple blades.

5.2.2 Propeller cavitation

Propeller cavitation is the single biggest sound problem of propellers since it is often dominates noise source. If a propeller starts to cavitate the noise increases considerably. To keep the noise low, propeller cavitation must be avoided. To suppress propeller cavitation the best design is to decrease pressure differences that the propeller is creating. This can be done by decreasing the propeller speed, decreasing the pitch or increasing the blade area ratio. All these interventions in the propeller
geometry decreases the pressure difference as well as smoothing pressure evenly spread over the blades. These considerations advocate that the optimal propeller design to avoid cavitation would be a propeller with low angular speed, low pitch and a large blade area to spread out the pressure.

When cavitation is initiated it is often located at the tip of the blade since the blade speed at the tip is the highest. There are two methods to deal with this problem, first to reduce the risk of tip cavitation is to make the blade tip relieved. Thus, the propeller blade have a pitch distribution over the blade with a high pitch at the propeller hub and a low pitch at the blade tip. This kind of distribution makes the pressure more even with less risk of tip cavitation. Another design that prevents tip cavitation is the skew angle. The skew angle helps with pressure distribution and prevent pressure fluctuations by evenly distribute the pressure. This helps by increasing the cavitation inception speed allowing for a higher speed before cavitation begins. The skewness of a propeller have a large beneficial impact on the sound generation.

5.2.3 Pressure fluctuation due to turbulence in wake field

Downstream at the propeller the turbulence of the wake from the hull hits the blades and creates pressure fluctuations that initiate cavitation. To deal with the wake field in a consistent way is beyond the reach of this project and is therefore neglected in the design process. However, to decrease the pressure fluctuations in the wake field the addition of blades to the propeller is a viable option. With more blades the pressure fluctuations decreases, which leads to the propeller producing less noise. As discussed before, a large skew angle is also beneficial in reducing the pressure fluctuations.

5.2.4 Propeller vibrations

Propeller vibrations causes noise from the propeller. To avoid vibrations from the propeller it is important to minimize the pressure fluctuations. This can be done by increasing the number of blades on the propeller and adding a large skew angle. This will minimize the induced vibrations by the propeller. One phenomena that can occur with blade vibration is that the vibrations match the natural frequencies of the propeller. When this happens the blade can start singing, to prevent this the propeller geometry can be altered by adding anti singing edges. Anti singing edges is applied to the trailing edge of the propeller blade as illustrated in figure 5.2.1 [3].
Figure 5.2.1: Illustration of trailing edges along the trailing edge of the suction side of the blade [3].

5.3 Propeller Requirements

The limitation of the propeller design is that it must adhere to the existing propeller specifications. This means that it has to have the same size to fit in the existing duct and it has to generate the same propulsive force. Hence, the diameter was set to the same as the existing propeller. Other aspects of the design that is somewhat limited comes from the manufacturing limitations, because the blades in its original shape is a standardized blade from the manufacturer the wing profile, chord distribution and pitch distribution is standard for the blade with limited adjustability. The design parameter that are controllable is:

- Number of blades
- Pitch
- BAR
- Skew

The requirements that is applicable to the existing propeller are the same for the new. The craft must be able to reach the same design speed which implies that the propeller need to produce the same amount of thrust. This was calculated with the methods presented in equation 3.6 - 3.10 from chapter 3. The resulting thrust interval is calculated and presented in table 5.3.1.
Table 5.3.1: The interval of the required thrust when using the method presented in chapter 3, calculated with equation 3.6 and 3.10.

<table>
<thead>
<tr>
<th>Propeller requirements</th>
<th>Design speed [Kt]</th>
<th>Thrust [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimating drag</td>
<td>3.5</td>
<td>1070</td>
</tr>
<tr>
<td>Estimating efficiencies</td>
<td>3.5</td>
<td>1100</td>
</tr>
</tbody>
</table>

Other requirements that needed to be considered where that the dimensions has to be the same as the existing propeller and the angular velocity has to be compatible with the existing electric engine.

5.4 Propeller design

Designing a propeller is a complex task and often consist of multiple compromises. It is difficult to design an optimal propeller. Still, it is important to weight the possible design alternatives against each other, to achieve the design goals. The OpenProp software was used with the previously set of input alternatives, and from which it was possible to investigate the cavitation. This was made in an iterative process where the pitch distribution and the BAR of the propeller were changed in order to reach an acceptable design for both minimal cavitation as well as the required thrust. When the requirements were finally fulfilled, discussions with the propeller manufacturer started Steelcraft propellers to agree on the final design. Some final adjustments were done related to production of the propeller. This did not change the principal design of the propeller.

The changes made on the bespoke propeller relative to the existing is summarized in table 5.4.1. The number of blades where increased to reduce vibrations and to increase the generated thrust per rotation. The mean pitch of the propeller was increased to reduce the RPM at which the propeller was still generating the required amount of thrust. The BAR was reduced to increase the efficiency of the propeller. The skew angle was increased for the new propeller to reduce the pressure on the propeller blades leading to less cavitation and also to reduce vibrations in the propeller that tend to cause noise.
CHAPTER 5. PROPELLER DESIGN PROCESS

Table 5.4.1: Changes made to the existing propeller to make it more efficient and to produce less noise.

<table>
<thead>
<tr>
<th>Propeller design</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blades</td>
<td>+</td>
</tr>
<tr>
<td>Pitch</td>
<td>+</td>
</tr>
<tr>
<td>BAR</td>
<td>-</td>
</tr>
<tr>
<td>Skew</td>
<td>+</td>
</tr>
</tbody>
</table>

The bespoke propeller is presented as a 3D-rendering in figure 5.4.1 below.

![3D rendering of new propeller](image)

Figure 5.4.1: 3D rendering of new propeller.

From the 3D rendering the manufacturer produced two propellers accordingly. In figure 5.4.2 the two different designs are placed next to each other. The different geometries are clearly visible.

![Existing and bespoke propeller](image)

Figure 5.4.2: The existing and bespoke propeller put next to each other. Illustrating how the geometries has been changed.
Chapter 6

Measurement of noise

The design of the field trial for the sound measurement was based on signature measurements made by NATO, see Carlton [6]. The procedure applied was to a large extent similar to Svedendal et al. [27]. The field trials were discussed with operators at JFD to match the requirement of noise measurement with practical and safe handling of the Carrier. The NATO trials, STANAG No. 1136, is a standard agreement used to measure noise from Surface Ships, Submarines, Helicopters, etc [6]. The second method was developed by FOI as a guideline for measurement of radiated noise from recreational boats [27].

6.1 NATO procedure

The test procedure used by NATO was developed with the purpose of sonar detection for torpedoes and war ships in particular. For this purpose, special test tracks were employed where the environmental conditions was sufficiently well known [6]. When following these procedures two hydrophones was used, one was placed directly under the path of the vessel and one was placed >100 meters to one side of the track. The purpose of the two hydrophones was to investigate different types of the radiated noise. One of the hydrophones was used to study the near field and the distant hydrophone to study the far field. The hydrophone located on the track of the vessel should measure the noise spectra at a frequency range of 10 - 1200 Hz. The second hydrophone measured a frequency range of 10Hz - 80kHz [6].

6.2 FOI procedure

The procedure presented by FOI was aimed towards investigating the acoustic signature from recreational boats [27]. Their approach was based on measurement standards for underwater noise measurements developed for commercial ships but
adapted to the size of smaller recreational boats [27]. For the actual test FOI used several different buoys to mark the Closest Point of Approach (CPA) to the hydrophone measurement locations. The CPA used by FOI were 10, 50, 100 and 300 meters, illustrated in figure 6.2.1 [27]. Each track was 500 meters long in total and conducted at different speeds of 5, 10 and 20 knots [27].

![Figure 6.2.1: Track setup for the initial FOI test procedure [27].](image)

For the test site area the following requirements should be fulfilled: the boat should be run in a straight line and at a constant speed and RPM. It should also be a quite area with a smooth and homogeneous seabed. When conducting the test the wave heights <0.5 m and no rain that will interfere with the measured signal. Further, background noise needs to be recorded. At the field trials background was obtained 30 minutes prior to the test [27].

For the FOI test procedure the following is applied, for the instrumentation and deployment: At least one hydrophone should be used and it should be placed at least one meter from the bottom and placed in a way that it being unaffected by wind and currents. If there is a buoy keeping the hydrophone in a vertical position it must be placed at >3 meters from the hydrophone. When deploying surface buoys and hydrophones their position should be measured with a GPS receiver and placed with an error margin of <5 meter [27]. An illustration of two different test rigs is presented in figure 6.2.2.
Figure 6.2.2: Illustration of different test rigs, either as autonomous (a) or surface connected (b) [27].

For the FOI test procedure the following is applied regarding the track: The track should be clearly marked with surface buoys for the CPA and at the start and finish of the track for easier navigation. The length of the track should be at least 500 meters. For the vessel being investigated a constant speed and RPM is important from the start to the end of the track, which is also important to keep track in the test protocol [27]. The different laps should be repeated at different speeds. To investigate directivity the laps should be repeated with the hydrophone to both starboard and port side of the boat described by figure 6.2.3 [27].

Figure 6.2.3: Description of the track and the vessels relation to the hydrophone [27].

### 6.3 Tests methodology

Based on the two test procedures previously presented a preliminary test was performed with the Carrier where it performed a few tracks to test the methodology. The experiences from the test lead to changes from the original plan that yielded a final methodology that was adapted to weather conditions, maneuvering of the carrier
and expected noise levels. The test track that was finally chosen is illustrated in figure 6.3.1. With the two triangles representing the track marker buoys that were placed approximately fifty meter on either side of the hydrophones. The circles represents the placement of the hydrophones H1 being the ST300 and H2 the ST500 hydrophone.

![Diagram of test track design]

Figure 6.3.1: Test track design.

Based on the NATO procedure one hydrophone was placed close to the track, H1 in figure 6.3.1 and one to the side of the track, H2 in figure 6.3.1 [6]. In order to both measure the far field of the noise and to aid with data points when the transmission loss (TL) was estimated. The distances were adapted to the noise properties of the Carrier. The distance from the track for the far field hydrophone (H2) was shortened from >100 meter that was specified by the NATO procedure [6] to 20 meters. This was done because of the expected SPL from the trials was lower than sounds expected from large warships. From the FOI procedure the concept of measuring for different speeds were taken.

### 6.3.1 Environmental categorization

Before a test location can be chosen preparations and investigations needs to be performed related to the location of the tests. Potential test sites were chosen from a sea-chart that were sufficiently deep, within the proximity of JFDs location on Rindö and also with a limited amount of traffic to minimize disturbances when the tests were performed. After some studies of the waters around JFDs location on Rindö and discussions with the operators of the boat two potential test sites where chosen for
further investigation. Those where the bay of Skarpö presented in figure 6.3.2 a) and the bay of Myttinge in figure 6.3.2 b).

(a) Bay of Skarpö [1].  (b) Bay of Myttinge [1].

Figure 6.3.2: Potential test cite locations.

The next step in the environmental categorization was to conduct a sediment investigation of the bottom conditions. This was done to make sure that the sediment was not too soft leading to the hydrophone sinking down in the mud. From the sea charts it is noted that both of these locations have clay bottom. On a rope with an anchor a camera and a flashlight was mounted to record when the anchor hit the bottom. This procedure provided an indication on the quality of the bottom sediment. The setup of the camera and flashlight is presented in figure 6.3.3.
The bottom was investigated at different locations in the two bays in order to provide a representative picture of the type of sediment. From the video recordings it was noticed that the conditions on both of the locations were good with a slight favor for the bay of Skarpö, being harder than the bay of Myttinge yielding better conditions for placement of the hydrophones. Another aspect is that the bay of Skarpö being closer to the location on Rindö where JFD is located. The result from one of the recordings from the bay of Skarpö is presented in figure 6.3.4.
small cloud of sediment particles visible in the upper parts of the picture. During this procedure the anchor hit the bottom several times on each location before it was raised 1-2 meters before it got dropped again.

Other aspects that is related to the environmental categorization was the weather conditions on the day of the tests. Waves and wind are desirable to keep to a minimum and rain is not favorable, because the broad band sound it generate will interfere with the recorded noise from the carrier.

6.3.2 Rig Design

The design of the test rigs were based on knowledge gained from the environmental categorization and the reports by FOI [27]. Two test rigs were designed, one for H1 and one for H2. H1 was placed in a position so that the Carrier could pass directly over it. The test rig for H1 had, thus, two buoys when it was placed on the seabed and made operational. When it was deployed it had three buoys since the test track is placed accordingly to its location. In figure 6.3.5 is an overall view of the test rig for H1 presented.

![Test rig diagram](image)

**Figure 6.3.5:** Test rig for H1 with specification of the parts included.

The small buoy above the hydrophone in the right side of the figure kept the hydrophone in a vertical position under the surface similar to figure 6.2.2. It was mounted 3 meters above the hydrophone to avoid potential disturbances of the noise produced by reflections from the the air volume of the buoy. [27]. The yellow rope
that was attached to the small buoy through a shackle runs up to the surface and was used to locate H1 when the other track marker buoys were placed. This was the third buoy that was removed before the rig went operational. The last buoy in the figure is the surface marker buoy that is attached to an anchor and from there attached to the same anchor as the hydrophone. The blue rope had a positive buoyancy so to allow for the hydrophone to be recovered if the surface buoy were lost for any reason. All of the knots was also secured with tape to avoid sound generated by the knots moving at the buoys and anchors. The test rig used for H2 consists of two buoys. Similarly to the H1 test rig there is one small buoy located 3 meters above the hydrophone to keep it in an upright position in the water. Since this hydrophone was located to the side of the track it suffice to have only one surface marker. It was important for the buoys to maintain their positions in the water during the test. Wind and waves could move the surface marker from their original positions. To avoid this the rope was allowed to run through the buoy with a weight on the opposite side making sure that the line remained stretched throughout the test. The arrangement is presented at the line attachment of the surface buoy in figure 6.3.6. This arrangement was applied to all surface buoys that were used.

Figure 6.3.6: Test rig for H2 with specification of the parts included.
6.3.3 Test protocol

In the protocol that was employed during the tests, information about the runs was noted as well as information about the surroundings and the environment. Environmental aspects that was taken into consideration was air temperature, wind speed and direction and wave height. Information about air temperature, wind speed and direction was taken from the Swedish Meteorological Institute (SMHI) website at the day of the test. The water temperature was logged by the ST300 hydrophone. Other information that was taken into consideration was the time for different operations such as, deployment of hydrophones, Carrier arrival time, the start and stop of the tracks and finally the time of the recovery of the hydrophones. The hydrophone recordings were time stamped when programmed for the tests using a PC. The time stamped data were recovered from the hydrophones and later CPA was identified paring tracks and hydrophone data. During the test a time was recorded when the Carrier entered the test site and then another one when it left. In between test runs the surroundings was kept under surveillance and any activity was noted in the protocol. Protocols are attached as appendix A.
Chapter 7

Analysis

In the following chapter the analysis is described for both the measured propeller noise and obtained propeller efficiency. The result constitutes the base for a comparison between the existent and the bespoke propeller.

7.1 Propeller Noise

The sound profile of the Carrier Seal was recorded with two hydrophones as described in section 6.3. From the recorded noise different sources were discovered, originated from the bow and stern of the Carrier Seal. To isolate the noise generated by cavitation signal was analyzed from a time segment close to the CPA for each test run. The recorded segment was initially stored in an WAV-file format with a sampling rate set to 96kHz. For data processing purposes the MATLAB function `audioread` was used to read the WAV-file and to process it. The `audioread` function returns the sample frequency and the sampled data [18]. The sampled data from the two hydrophones were then calibrated with the provided values from the manufacturer, see table 2.2.1. To convert the WAV file into units of $\mu Pa$ the following code was used:

```matlab
[y, Fs] = audioread(filename); % read wav data from file
cal = 135.4; % value from calibration sheet
cal = power(10, cal / 20); % convert cal from dB into ratio
y = y * cal; % multiply wav data by cal to convert to $\mu Pa$
```

Time segments from the the test runs were identified and the broadband energy of the segments were determined using the RMS method. The mean amplitude of the RMS time segment was used to determine the SPL for that particular segment. When the broadband energy for each test was determined the constant $A$ for the transmission loss was estimated. Because of varying accuracy from the positioning equipment on the Carrier not all of the conducted trials could be directly used. For the occasion when
the accuracy was low another method was applied to determine the Carriers position. Then the initial bearing when it approached the test track was used and it was assumed to be constant when the Carrier was within the test track. From the different trial runs the distance between the propeller and the hydrophones for different positions along the track was calculated. Together with the corresponding SPL the transmission loss constant A from equation 2.5 was estimated. Knowing the transmission loss, the distance from which \( SE = NL \) was determined, which corresponds to the distance at which the vessel is barely detectable. Another aspects of the transmission loss was that it allows for the measured noise to be referenced to 1 m distance between the Carrier and the hydrophones thereby putting the test tracks on the same footing and yielding source levels that were comparative between the test runs.

The measured noise levels obtained at CPA were subsequently referenced to 1 m distance, which is the definition of the source level. The power spectral density (PSD) was calculated using the Welch method. A 50% overlap and a Hanning window function were used [19]. The units resulting from the PSD was \( p^2 / Hz \) rel \( 1 \mu Pa \) [19]. A segment length of one second was chosen resulting in unit of \( p^2 \) rel \( 1 \mu Pa \). This choice is convenient since it can be compared to broad band levels and amplitudes of sinusoidal tones.

### 7.2 Propeller Efficiency

To investigate the efficiency of the bespooken and existing propeller, equation 3.10 was used. The test procedure was done for multiple velocities. By doing the same test procedure for both propellers a quotient between existing and bespooken propeller efficiencies could be calculated for different velocities. Test runs with same velocities can be compared since the required torque was constant for such conditions. Thus, resulting in a change of input thrust and propeller efficiency. The power input from the thrusters was logged and stored for all tracks. The efficiency quotient between the existing and bespooken was calculated using

\[
\frac{\eta_{\text{Bespooken}}}{\eta_{\text{Existing}}} = \frac{P_{m\text{Existing}}}{P_{m\text{Bespooken}}},
\]

where \( \eta_{\text{Bespooken}} \) and \( \eta_{\text{Existing}} \) are the propeller efficiencies for the bespooken and existing propeller and \( P_{m\text{Bespooken}} \) and \( P_{m\text{Existing}} \) are the engine thrust of the propellers. Note that when the quotient between bespooken and existing propellers is larger than one, the propeller efficiency have been increased by the bespooken compared to the existing propeller.
Chapter 8

Results

The results were based on measured data from the trials. The data was analyzed according to methodology outlined in chapter 7. The trials were performed for the existing propeller and for the new propeller. The results are discussed below.

8.1 Position data

The position of the Carrier was logged as it was running. When possible the position was logged using GPS but when underwater the Carrier relies on a Doppler Velocity Log (DVL) to calculate its position. The DVL position can sometimes drift resulting in large positioning errors which was the case in some of the test runs. For those data was discarded. The navigation errors were identified by observations of large jumps in position when the seal carrier received a correct GPS position on the surface. It was also encountered that the DVL did not get sufficiently accurate readings causing the presented track to move in irregular ways. This error was resolved by using the Carriers initial bearing to estimate its position.

In figure 8.1.1 the trajectories for two test runs are shown, one good run and one bad run. The latter with a drift in position. The trajectory of the good test run is fairly straight with no large changes in position when the carrier surfaced and received its GPS position. During the bad test run the position changed with about 20 meters when the carrier surfaced. Since there is no way to identify when the drift occurred the test run was classified as unsuccessful.
CHAPTER 8. RESULTS

Figure 8.1.1: Trajectories for two different test runs with the drift resulting in the jump presented at the end of the run.

A second aspects that resulted in discarded test runs was if the course was not straight enough. The crew onboard kept the heading constant and the track should be fairly straight. In some cases the navigation system drifted and the apparent track was semi-circular making it difficult to determine CPA. Figure 8.1.2 shows the resulting trajectories of a straight and curved test run. At the location of the hydrophone there is a clear CPA on the good test run no clear CPA on the bad test run leading to the bad test being discarded.

Figure 8.1.2: Trajectories for two different test runs with the deviation from the desired course resulting in no clear CPA for the bad run.

The third error that occurred was that the data from the DVL was insufficient causing the track to move irregularly. In figure 8.1.3 it is illustrated how the track moved and how the bearing for the tracks was estimated.
8.2 Transmission Loss

The transmission is described by equation 2.5 and the constant $A$ was estimated from the inclination of line generated from various data points for the trials at four and five knots for both propellers. Figure 8.2.1 shows how the noise attenuates over a distance. The mean value of the attenuation was found to be 17.5 and it is presented by the line referred to as Reference: $A = 17.5$ in the figure. The Source Levels presented in this thesis is not the absolute SPL measured during the trials. The values have been shifted. However all Source Levels have been shifted equally and thus it allows for a comparison to be made between the bespoken and the existing propeller.

Figure 8.2.1: Figure showing the broad band amplitude over the logarithmic distance from the source. Meaning that the amplitude at $\log(r) = 0$ represents the source level. (Not actual amplitude values)
8.3 Power spectral density

The Power Spectral Density (PSD) was calculated for each speed that was being tested to allow for a comparison of the frequency content, both to find differences between the existing and the bespoke propeller but also to study differences at different velocities. The test was performed at 3, 4 and 5 knots. The spectra for each speed is presented in figures 8.3.1-8.3.3. Each spectrum was compensated for transmission loss and is presented as source level at 1 m distance. The amplitude of the spectrum is not representing the broadband SPL thus only allowing for a comparison between the propellers and the different speeds and not the actual power of the signal.

**Speed: 3 knots**

![Figure 8.3.1: PSD plot showing the frequency content of the broadband signal from the carrier seal propelled at 3 knots. (Not actual amplitude values)](image)
CHAPTER 8. RESULTS

**Speed: 4 knots**

![PSD plot showing the frequency content of the broadband signal from the carrier seal propelled at 4 knots. (Not actual amplitude values)](image)

**Speed: 5 knots**

![PSD plot showing the frequency content of the broadband signal from the carrier seal propelled at 5 knots. (Not actual amplitude values)](image)
8.4 Broadband

From the broadband signal the source level (SL) can be calculated with the help of the sonar equating that is shown in equation 2.2. The full broadband covered 0 to 3000 Hz. The full band was divided into two sub-bands covering 0 to 200 Hz, 200 to 3000 Hz and The lower band contains the tones whilst the upper band the cavitation and propeller signing.

Table 8.4.1: Showing the change in source level between existing and bespoke propeller for different speeds and frequency regions

<table>
<thead>
<tr>
<th>SL change</th>
<th>0-200 Hz</th>
<th>200-3000 Hz</th>
<th>0-3000 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 knots</td>
<td>-4 dB re 1μPa</td>
<td>0 dB re 1μPa</td>
<td>-1 dB re 1μPa</td>
</tr>
<tr>
<td>4 knots</td>
<td>-6 dB re 1μPa</td>
<td>-2 dB re 1μPa</td>
<td>-3 dB re 1μPa</td>
</tr>
<tr>
<td>5 knots</td>
<td>-11 dB re 1μPa</td>
<td>+1 dB re 1μPa</td>
<td>0 dB re 1μPa</td>
</tr>
</tbody>
</table>

8.5 Background sound

The background sound was recorded before the trials where conducted and used to verify that the measured noise level is significantly different from the background. The sound from the background is referred to as NL in equation 2.2. With the incoming parameters the change in distance at when the Carrier is barely detectable can be calculated. These values are then compared between the two propellers when operated at the same speed. In table 8.5.1 the decrease in distance is presented for the different speeds the Carrier was operated at.

Table 8.5.1: Showing how the distances at when the Carrier is barely detectable (SE=0) decreased for the different speeds.

<table>
<thead>
<tr>
<th>Speed</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 knots</td>
<td>16 %</td>
</tr>
<tr>
<td>4 knots</td>
<td>33 %</td>
</tr>
<tr>
<td>5 knots</td>
<td>5 %</td>
</tr>
</tbody>
</table>
8.6 Propeller Efficiency

The efficiency was determined as a relative value between the existing and bespoke propeller. The Carrier is logging the engine output and speed. These values can then be used as input to equation 7.1, the difference in efficiency was determined for different speeds.

Table 8.6.1: Showing the efficiency improvement from the existing to bespoke propeller for different speeds

<table>
<thead>
<tr>
<th>Speed</th>
<th>Efficiency change</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 knots</td>
<td>10-15 %</td>
</tr>
<tr>
<td>4 knots</td>
<td>10-15 %</td>
</tr>
<tr>
<td>5 knots</td>
<td>20-30 %</td>
</tr>
</tbody>
</table>

8.7 Errors

The largest error that occurred is because of the distance between the vessel and the buoys gets wrong. Leading to that the signal reaching the hydrophone gets wrong. These error exists for both when the position is given from the GPS/DVL and when an assumed bearing is used. Another error is the GPS accuracy of ±3 meters.
Chapter 9

Discussion

In the following section the results will be elaborated on and conclusions will be drawn. Errors and uncertainties related to work will also be discussed. Finally a suggestion for future work is made.

9.1 Propeller design process

In the design process the main focus was to develop a silent and efficient propeller for the carrier. The design improvements regrading the noise generation was made on a conceptual level. An investigation was made into the different aspects of the propeller design that would effect the noise generation. These findings was used to guide and improve the design to achieve a silent propeller. The conceptual design, to make the propeller produce less noise, was then combined with theory on propeller efficiency. The two design goals were in many cases contradiciting to each other; by making the propeller more efficient will lead to a nosier propeller. One of the major noise generating phenomenon off the propeller is cavitation. To make the propeller as silent as possible the cavitation should be kept at a minimum, buy removing cavitation of the propeller sacrifices the efficiency. The optimal propeller in both perspectives would therefore operate on the limit of the cavitation inception speed, where the propeller start to experience cavitation. The design process therefore in large part consist of finding these design compromises and find a near optimal solution.

Four major geometric changes was done to the bespoke propeller compared to the existing. Number of blades, skew, pitch and BAR. The number of blades and skew were increased as a result of conceptual design ideas to reduce noise. The impact on the efficiency off these changes was low which made it favorable to add as many blades a possible and add a large skew angle. The changes to pitch and BAR were more challenging in order to fulfill with both design goals. A large BAR is preferred to reduce
cavitation which reduce noise, but efficiency is increased with a lower BAR. To achieve a high efficiency while emitting low noise the cavitation margin would need to decrease to keep a safety margin of cavitation. To determine a cavitation margin the existing propeller was modeled and the theoretical cavitation number was calculated. For the operating conditions it was modeled that the existing propeller had a low probability to generate cavitation, as well as that the existing propeller had a high cavitation margin. The bespoken propeller design could therefore have a similar cavitation margin while making the conceptual changes to reduce sound. With similar cavitation margins of the bespoken propeller, the conceptual design was expected to increase. In this project one aim was to maintain the operating speed and thus the pitch was used in the design process to adapt thrust to at least reach the same as with the existing propeller. The design process was an iterative process. Several propeller design concepts were generated and the one option was finally picked for the operating conditions that was specified for the Carrier Seal.

9.2 Resulting Noise Generation

The results from the trials show that the sound spectrum from the propeller was evened out for the whole propeller spectrum. This applies to the speed range of the propeller and is clearly visible in figures 8.3.1-8.3.3. The spectrum was divided into two intervals. For frequencies <200 Hz the noise consisted of distinct tones and at frequencies >200 Hz the noise had a broadband structure with some tones.

Frequencies below 200 Hz

The noise that were generated at frequencies below 200 Hz was mainly related to the propeller blade tones that are caused by the rotational speed of the propeller and number of blades. In the figures 8.3.1-8.3.3 the tones that are generated are directly related to the propeller blade tones and its harmonics. For the bespoken propeller the propeller blade tones are not as pronounced as for the existing propeller. The underlying reason for this is directly related to the propeller design. The increased number of blades results in each individual blade being under less force that suppresses the tones. The high skew angle and the pitch reduce the pressure differences on the blades at the tip of the propeller blade that likely decreases the propeller blade tones. The exact phenomena behind the reduced blade tones can not be determined but overall the bespoken propeller have blade tones that are reduced by 10-20 dB re 1 $\mu Pa$ over the speed range that is a vast improvement corresponding to a reduction of the sound pressure with 90 % at 4 knots.
Frequencies above 200 Hz

Frequencies above 200 Hz are mainly related to propeller cavitation that appears as a hump at around 1 kHz for speeds at four to five knots, see figure 8.3.2 and 8.3.3. At three knots shown in figure 8.3.1 it is not as pronounced. The hump may be the initial start of cavitation, but without further analysis it cannot be explicitly determined. The cavitation that is still present is probably produced by the increase in pitch of the bespoken propeller. It was designed to be significantly more aggressive than the existing propeller in order to be retain efficiency. Initial modelling of the theoretical cavitation value indicated that neither of the two propellers would generate cavitation. This was later discovered not to be the case that is probably related to the duct and/or flow around the hull generating turbulent conditions hitting both propellers.

Propeller singing was identified in the measured data. For the existing propeller it occurs at approximately 430 Hz and yields an amplitude of about 265 dB re 1 $\mu$Pa and for the bespoken propeller singing appears at 300 Hz and with a resonance frequency at 600 Hz with an amplitude reaching approximately 245 dB re 1 $\mu$Pa. Note again that these values are not absolute. The scale has been shifted. However, it allows for a comparison between the two propellers.

Broadband noise

The difference of the broad band signature from the two propellers it was observed that the emitted noise was lower in the whole frequency region and for all speeds. However, cavitation was higher at 5 knots as shown in table 8.4.1. At the design speed of four knots the SPL of the emitted noise was reduced by 3 dB re 1 $\mu$Pa, corresponding to a reduction in sound pressure by 40%. The detection distance of the Carrier was reduced by 33 % for the prevailing conditions at the trial site, see figure 8.5.1.

9.3 Propeller efficiency

The bespoken propeller was more efficient than the existing propeller, see table 8.6.1. There was an observed efficiency increase for all speeds, with higher efficiency at higher speed. This is contributed to the bespoken propeller made more aggressive than the existing, which resulted in a lower propeller speed that allowed for a lower BAR. For the bespoken propeller cavitation start earlier than the existing propeller. The reason behind this behavior is that the propeller was designed to have a higher efficiency, resulting in it being closer to the cavitation margin than the existing propeller. Solutions to this problem might be to change the operating condition by changing the wake field at the propeller, making the flow less turbulent which would lead to less cavitation. If the operating condition can not be changed, the only
option is to change the propeller itself. By increasing the BAR and lowering the pitch the cavitation margin could be higher, but it will probably lead to a decrease in the efficiency of the propeller.

The data used for the calculations of efficiency are directly based on measurements from the test tracks and no specific tests were done for estimating the efficiency. The test track was not the ideal test conditions as the carrier only achieved equilibrium state for a short period of time. This implies that the efficiencies should be taken as an initial estimate and for a more accurate estimates dedicated experimental test should be designed and conducted.
Chapter 10

Conclusion

From the field trials that were conducted it can be concluded that the bespoke propeller emits significantly less noise than the existing propeller and consuming less energy. The theories applied during the propeller design process have proven themselves to be valid in producing a propeller that emits less noise. At this stage we as authors would recommend JFD to change their propeller to this bespoke one as there are only advantages with it compared to the existing one.

10.1 Future Work

This study was limited both in time and in resources and should be regarded as a starting point. A continued study of the cavitation is necessary, especially to determine the cavitation inception speed. The modelling should be improved so to allow for finding a design that can be realized and tested. Probably this will require a switch to more advanced models. The recommended focus is to investigate the cavitation inception speed and to shift it as high as possible without compromising efficiency. Another prosperous way forward is to take the actual vessel into account and especially to study the effect of the Carrier’s hull on the performance of the propeller.

In this study the duct and the location of the propulsion were given by the present design of the Carrier. Future work could investigate how to change the geometry of the duct and their placement on the hull. Finally to resolve the question on the hull and propeller interaction, a specific study of the hull wake should be made.
Bibliography


# Appendix A

## Test protocol

### A.1 Test 1 (240422)

Protocol from the first test in Swedish.
<table>
<thead>
<tr>
<th>Passage</th>
<th>Anm.</th>
<th>Fart [kn]</th>
<th>RPM</th>
<th>Startboj</th>
<th>Slutboj</th>
<th>Anmärkning</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>3 500</td>
<td></td>
<td>14:18:14</td>
<td>14:19:55</td>
<td>Eventuellt se körning</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>3 500</td>
<td></td>
<td>14:26:02</td>
<td>14:27:22</td>
<td>14:26:17 nere under vattnet något sent</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>4 600</td>
<td></td>
<td>14:34:39</td>
<td>14:36:06</td>
<td>15:06:44 Kajak vid h1</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>4 600</td>
<td></td>
<td>14:48:19</td>
<td>14:49:40</td>
<td>15:07:07 Båt i testområde</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>5 700</td>
<td></td>
<td>15:04:08</td>
<td>15:05:28</td>
<td>15:09:25 Båt lämnar område</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>5 700</td>
<td></td>
<td>15:12:52</td>
<td>15:13:57</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td></td>
<td></td>
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<td></td>
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<td>15:18:59</td>
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</table>