Condition Monitoring (CM)

Concept selection of sensors for monitoring of mechanical wear

---

Tillståndsövervakning (CM)

Konceptframtagning av sensorer för övervakning av mekaniskt slitage

---

Hampus Vinblad

Institutionen för Ingenjörsvetenskap och Fysik

Högskoleingenjörsprogrammet i Maskinteknik

22.5 HP

Jan Erik Odhe

Anders Biel

2022-06-01

1

- Intentionally blank page -

Abstract

This bachelor thesis has been executed with the product development process double diamond. The thesis has been performed at Karlstad University in cooperation with Kongsberg Maritime in Sweden AB. The objective of the thesis has been to develop a condition monitoring system for Kongsberg's waterjet department. Substantially it has to do with finding a system which could monitor wear and problematic trends in the hydraulic oil and oil lubricated bearings. The wear is to be translated to an electrical signal which could be used to alert and visualize the wear to the end user.

The literature study was divided into two parts. The first part of the literature study consisted of analyzing and understanding wear and condition monitoring systems. The second part of the literature study instead consisted of analyzing different kind of measurement methods which could be suitable for so-called online measurements. The used references come from scientific articles and documents publicized by various classification societies.

The final solution consists of a system of different sensors and measurement methods. Due to the fact that the system is to be installed on ships, the system needed to be considered with rules from various classification societies. The rules which are relevant for the project was placed in an elimination matrix where concepts that didn't live up to the rules were scrapped. Further on, the sub concepts were evaluated and selected with a relative matrix and a weighted Kesselring matrix, which gave the most suitable sub concepts. The sub concepts were merged into a complete condition monitoring system at concept level. The final system solution could measure solid particles in oil, humidity in oil, oil flow, torque, rotational speed of the shaft and vibrations. The selected sensors also enabled the system to measure shaft power, oil conductivity and oil permittivity which were not included in the task.

- Intentionally blank page -

Sammanfattning

Examensarbetet har genomförts med hjälp av produktutvecklingsprocessen double diamond. Arbetet har genomförts på Karlstad Universitet i samarbete med Kongsberg Maritime in Sweden AB. Målet med arbetet har varit att ta fram ett tillståndsövervakningssystem till Kongsbergs vattenjet avdelning. I huvudsak har det handlat om att hitta ett system som kan övervaka slitage och problematik i hydraulikolja och oljesmorda lager. Slitaget skall med hjälp av sensorer översättas till en elektrisk signal vilket kan programmeras till felmeddelanden som i sin tur kan visualisera slitage till slutanvändaren.

Litteraturstudien till arbetet delades in i två delar. Den första delen av litteraturstudien bestod av att analysera och förstå slitage och tillståndsövervakningssystem. Den andra delen av litteraturstudien bestod av analysering av olika mätmetoder som kan vara lämpliga för så kallad on-line mätning. Referenserna som användes kommer från vetenskapliga artiklar och dokument som blivit publicerade av diverse klassningsbolag.

Den slutgiltiga lösningen består av ett system med olika sensorer och mätmetoder. Med anledning av att systemet skall användas på fartyg så behövde regelverk från diverse klassningsbolag tas i beaktande. De regler som kunde vara relevanta för projektet lades in i en elimineringsmatris där koncept som inte följde regelverket sållades bort. Vidare så genomfördes konceptutvärderingen med en relativ matris och en viktad Kesselring matris vilket gav de mest lämpade delsystemen. Delsystemen har sedan under designfasen satts ihop till ett komplett tillståndsövervakningssystem på konceptnivå. Den framtagna lösningen kan i huvudsak mäta partiklar i oljan, vatten i oljan, oljans flöde, vridmoment, rotationshastighet på axel och vibration. Utöver de parametrar som system var designat att mäta har även flertalet andra parametrar tillkommit såsom effekt, oljans konduktivitet och oljans permittivitet.

Content

1 Introduction

1.1 Background

Humans' behavior and their sights of the world have changed dramatically over the last decade. Countries and humans have gone from a relative self-sufficient life to a life that is depending on trading with goods all over the globe. Peoples transport habits have also changed from transporting with emigration in mind to transport and traveling for entertainment and pleasure. The so-called globalization has led to millions of supplies passing the country's borders each day, either by ship, flights or by land with trucks or cars. One of the main reasons for the quick globalization is the accelerated technical development. The globalization hasn't just made it easier for humans and supplies to pass country boarders it has also enabled increasing information trades between the countries, which have aided an even faster technological advancement. For humans to be able to pass the boarders in a safe manner, the requirements on the transport companies safety thoughts have increased drastically. A breakdown which endangers humans' life could potentially lead to an economical disaster for the company who constructed the craft. To avoid failures the construction companies invest a huge amount of money to develop several systems to decrease the risks of a so-called functional failure.

The vehicle industry, which are in the front edge of this development, is using measuring methods which can visualize to the user that the brake pads are worn out or that the tire pressure is too low. The visualization occurs with a fault code and a fault message on the instrument cluster which recommends the user to take action to reduce the risk of an accident or a functional failure.

The ship industry has fallen a little bit behind on this development. Even though millions of people in one way or another are depending on the ships operational reliability there are only a few methods or systems used to measure equipment wear. The wear could potentially lead to a functional failure which could cause delays and cancelations which in the end could cause huge economical and reputational damages to the shipping company. By using Condition Monitoring (CM) systems the ship could be considerably more reliable. With an CM-system the user could in an early stage understand that an abnormal wear has arisen and could therefore take quick actions to avoid a functional failure which eventually could damage even more components or equipment on the ship. A CM-system could also enable the shipping company to easier plan service visits once the ship is docked or out of service for other reasons, which decreases indirect cost for the shipping company.

Kongsberg Maritime Sweden AB in Kristinehamn, could in their concern, deliver complete propulsion-systems for ships. The products are mainly used for large scale applications such as commercial ferries, yachts and tankers. Kongsberg primarily works with propellers, waterjets and control systems for those. The thesis will primarily be aimed towards the waterjet department but also the control system department will be partially involved.

Waterjets is a product which transfers rotation movement to a waterjet with an impeller and a nozzle, see figure 1. The waterjet creates a force aimed straight backwards in the ship's direction and according to Newtons third law, all forces acting in one direction must have a reaction force in the opposite direction. In waterjet applications it is the reaction force that makes the ship move forwards.

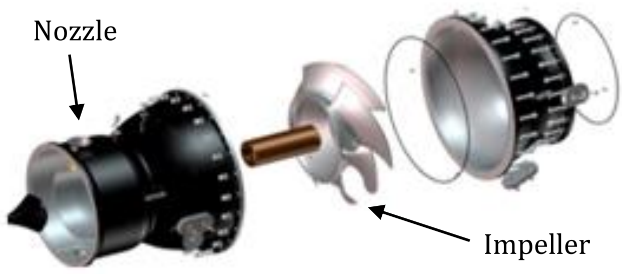

Figure 1, exploded view of the impeller housing.

The water which will later become a waterjet comes from the bottom of the ship's hull through a so-called intake. The rotational movement which drives the impeller comes from a rotational engine. The rotational movement is being transmitted from the engine to the impeller with shafts, bearings and seals. Inside the impeller housing there is pump bearing which is designed to distribute forces created by the waterjet. The pump bearing is filled with pressurized hydraulic oil and together with a mechanical shaft seal it is supposed to keep the water and oil separated.

To control the waterjet direction, a steering module is used, see figure 2. The waterjets also have a so-called reversing bucket which covers the waterjet and turns its direction so that the force from the waterjet instead acts in the opposite direction. The steering module and the reversing bucket are being controlled with hydraulic cylinders which are part of a hydraulic system designed for the waterjet application. The hydraulic system could be controlled with electrical signals from the control system which enables the captain to steer the ship from the control bridge.

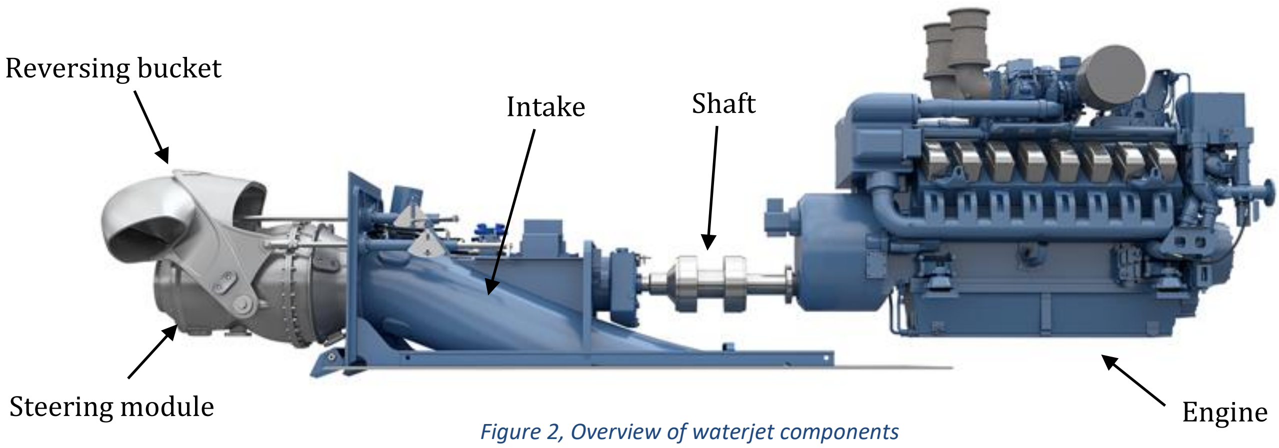

Figure 2, Overview of waterjet components

1.2 Purpose

Kongsberg waterjets uses a so-called MTBO (Mean Time Between Overhaulin'), which means that service is being executed after a certain amount of driving time or after a certain number of years, depending on what occurs first. During the service an extensive overhauling is being performed on components that are suspected to be worn down, such as seals, bearings and other spare parts. Since some of the components are placed under the water surface it could be difficult for the service crew onboard to perform a visual inspection of the parts between the service intervals. The difficulties to visually inspect components under the water surface could potentially lead to a functional failure. Even though most of the parts are placed so that they could be visually inspected it could also be difficult to see if a component is worn out with the bare eyes. Due to this, Kongsberg Maritime wants to investigate the possibilities to find a system which could measure wear in their equipment and translate it to electrical signals which could be visualized to the user in their control system.

1.3 Goal

Kongsberg wishes to develop the mechanical part of a Condition Monitoring system with this thesis work. The CM-system shall be able to translate vibrations, torque, rotations speed of the shaft, water quantity in hydraulic oil and particles in hydraulic oil to electrical signals. The thesis works main focus is to develop methods and concepts on how those measurements could be performed regarding different materials, placement and different sizes on the products. The final solution must also consider IP-classes, heat generation and electromagnetic disturbances. For the final solution to be applied on conventional ships the work also needs to consider rules from classification societies. Below is a list of relevant classifications and their prioritization. DNV classification are to be seen as mandatory while BV and ABS are to be seen as prioritized. The rest of the classifications are to be seen as wished but not mandatory. A summary of the classification societies could be seen in table 1.

Table 1, summary of classification societies in interest

Classification society	Classification name	Short name	Requirement
DNV	Rules for classification High-Speed and light craft	RU-HSLC	Mandatory
BV	Rules for classification of steel ships	NR 467	Prioritized
ABS	ABS Rules for building and classing high speed craft	None	Prioritized
CCS	Rules for construction and classification of sea-going High-speed craft	None	Wished
RINA	Rules for the classification of ships	None	Wished
Loyds Register	Rules and regulations for the classifications of ships	None	Wished
Loyds Register	Rules and regulations for the classification of Naval ships	None	Wished

1.4 Limitations

The control box of the Condition monitoring system will be located inside the machinery space and will require a cabinet in order to not be affected by surrounding environments. Design of the cabinet will be part of the thesis work. In the task description there is a requirement that the developed system shall be compatible with the existing control system which will need to be taken into consideration in the work. How the electrical signals will be processed inside various control boxes, how the control boxes should be programmed and how further communications should occur, will not be part of this thesis work. Figure 3 clarifies what will be part of the thesis work and what should not be part of the thesis work. The thesis work will give answers on the questions why, where and how. This bachelor thesis could be used as a background to further investigations and development.

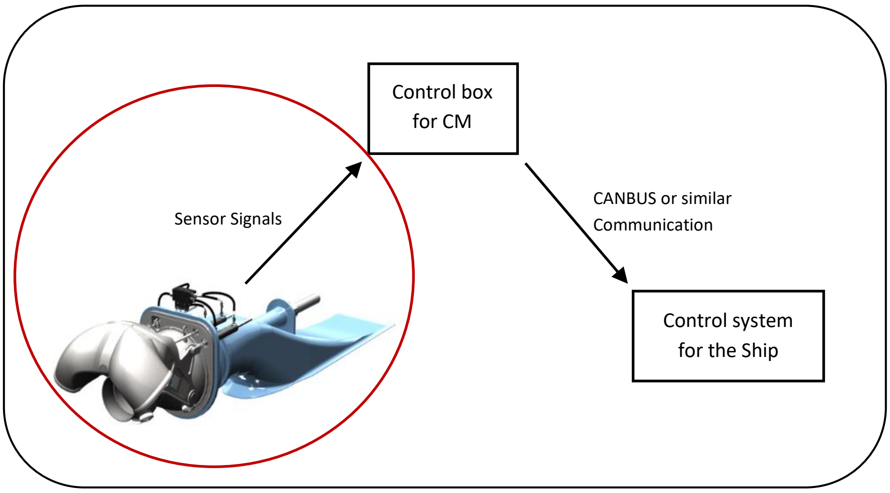

Figure 3, Overview of thesis limitations.

1.5 Special conditions

Kongsberg Maritime wishes to reserve the rights to exclude certain details in the final report. Those details could for example be product names and critical details that could be of interest for competing companies.

2 Method and Theory

The project will be executed accordingly the double diamond process for product development. The name double diamond comes from an idea of expanding and narrow down the perspectives twice which forms two diamonds as could be seen in figure 4. The idea is that the process starts on the left side with a problem or a task which needs to be solved. The two diamonds also represent a phase of research and a phase of design which could be further divided into discovery, define, develop and deliver phases.

Discovery phase is supposed to give a deeper understanding of the problem, deeper research on topics related to the problem and generally simplify the project. The mindset should be set to diverged thoughts which enables expansion of the perspectives.

The mindset of the define phase should instead be convergent which means that the thoughts should be more specific to the solution which means that the perspectives are narrowed down. At the end of the phase the requirement specification defines the framework of the project.

The third phase is the develop phase where ideas come to life in so-called concepts, which could be seen as potential solutions to the problem. The develop phase once again expands the perspectives where the concepts diverge from each other.

The last phase is the deliver phase. In the deliver phase it is time to evaluate the created concepts against the requirement specification. Once a suitable concept has been selected, the concept needs to be realized through computer aided programs, prototypes or other suitable methods. [1]

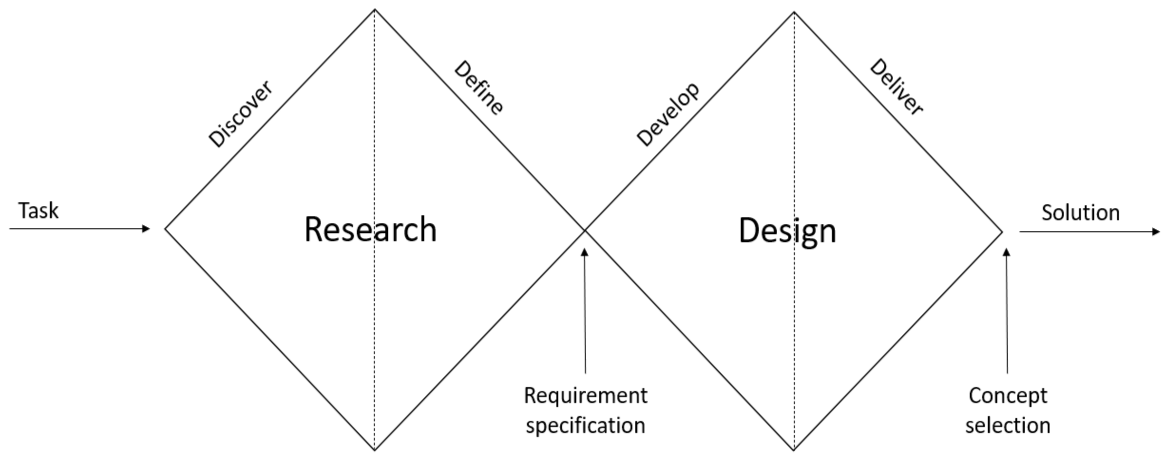

Figure 4, Illustration of the double diamond processes.
The figure is recreated from the Design council [1].

2.1 Project plan

At the beginning of the project a project plan was created to define the given task. The purpose of the project plan is to define the background, purpose, goal, limitations and conditions of the project in combination with defining a timeframe and involved people of the project. The project plan is a great way for the project owner and the project worker to confirm that their expectations of the project are equivalent. [2, p.35]

2.1.1 GANTT chart and WBS

The so-called GANTT chart is one of the most common methods for visualization of a project's timeframe. The timeframe of the project is illustrated on a horizontal axis while the phases or tasks are illustrated on rows below the horizontal axis. The phases are thereafter visualized as blocks which length is depending on estimated time. [2, p.33] The length of the phases which are to be decided in the GANTT chart could however be difficult to estimate why a so-called work breakdown structure (WBS) could be suitable to perform. The principles of a WBS are to hierarchically breakdown the product into all existing processes which enables a better understanding of all the tasks that needs to be performed. [2, p.24]

2.2 Requirement & Functional specification

2.2.1 Requirement specification

One of the most important documents in a project is the requirement specification. The document consists of several criteriums which are either a requirement or a desire on the product. The document also states if the criterium is a function or a limitation. In certain cases the criteriums could also be weighted which enables a better understanding of which criteriums that are important during the development. The weight could also enable a more precise evaluation process during the concept selection. [3, p.150]

2.2.2 Functional specification

A function specification is a process where the product functions is divided into main functions, subfunctions and supporting functions. The main function describes the main purpose of the product and could be seen as a requirement which the product must fulfill. For the main function to be fulfilled there must be subfunctions which also could be divided into supporting functions. The functional specification could be visualized with a functional tree and it could also be used as a support to the requirement specification. [3]

2.3 Concept generation and selection

2.3.1 Concept generation

The starting point for concept generation is according to literature the criterions from the requirement specification. The requirement specification will therefore serve as a framework to the concept generation. Since the developed product in this specific project is a system, it could be a good idea to already in the concept generation divide the system into sub concepts. This fact enables the possibility to pick the best sub concepts to receive the most efficient end product. The concepts are to be generated with concept sketches, handwritten and visualized in computer aided designs programs. The concept generation will mainly use the following methods: [3]

- Benchmarking.
- Idea association.
- The catalogue method.

Benchmarking

Benchmarking is one of the most common methods used in product development. Benchmarking means that the designer investigates the competitors' products, not only to copy but also improve their own product. Benchmarking will be performed in this project, both towards the shipping and wind turbine industry. [3, p.299]

Idea association

Idea association is a method where fantasy is used to achieve something constructive. The method is suitable for individual projects and could be used to associate your own or others' ideas. [3, p.171]

The catalogue method

One of the most rational methods is the so-called catalogue and literature method. It could be used to systematically investigate how others have solved similar or familiar problems. The method could also be used to find inspiration and ideas in a more unstructured manner. [3, p.173]

2.3.2 Concept selection

The concept selection process will be performed as described by Ulrich and Eppinger. The process consists of three distinct steps.

1. Elimination of concepts which does not comply with the requirement specification.
2. Concept screening with relative decision matrix.
3. Concept scoring with a criteria weight matrix.

The process is illustrated in figure 5. Furthermore, it is important to determine which methods that needs to be used to fulfill the three steps. [3, p.179-182]

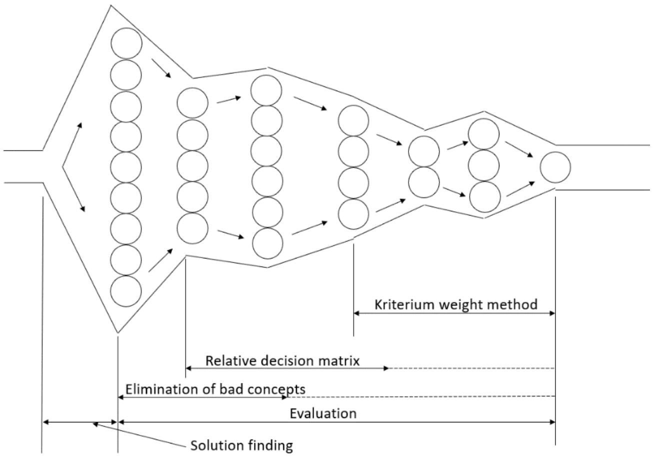

Figure 5, illustration of the evaluation process.
The figure is a recreation from [3].

Pahl and Beitz matrix

The Pahl and Beitz matrix is the first method used to evaluate the created concepts. The method is mainly used to eliminate poorly created concepts. The matrix consists of seven criteriums which all needs to be fulfilled to pass the first step of the process. The criteriums could the following:

- Does the solution solve the main problem?
- Does the solution fulfill all the requirements?
- Could the solution be realized?
- Is the solution within the cost frame?
- Is the solution advantageous in an environmental, safety and ergonomic perspective?
- Does the solution suit the company's product program?
- Is there enough information available for the solution?

If the concept passes the criterium, a positive symbol is added to that specific column and if the concept does not pass the criterium a negative symbol is added and the concept is eliminated. If further information is needed a question mark is added to the column and the evaluation continues. The same process applies to exclamation mark which indicates that the requirement specification needs to be controlled. [3, p.182-183] Figure 6 illustrates an example of the template used for the Pahl and Beitz matrix.

Page 1	Eliminationmatrix for:								
Solution	Solves the mainproblem	Fulfills all requirements	Realisable	Within costframe	Safe and ergonomic	Suits the company	Enough information	Comment	Decision
1	+	+	+	+	+	+	+		+
2	+	+	-						-
3	+	+	?	+	+	+	+		?
4									
5									
6									
7									

Eliminationcriteriums:
(+) Yes
(-) No
(?) More info required
(!) Control of requirement spec

Decision:
(+) Proceed solution
(-) Eliminate solution
(?) Seek more info
(!) Control requirement spec

Figure 6, Pahl and Beitz elimination matrix.
Recreated and translated from [3].

Pugh´s relative decision matrix

Pugh's relative decision matrix is a method where the concepts are compared to a so-called reference solution. The reference solution could be one of the created concepts, an existing solution or a competing solution. Where the last two examples are most common. The matrix consists of criteriums from the requirement specification where each criterium is evaluated against the reference product. If the evaluated concept fulfills the criterium better than the reference solution it receives a positive symbol, if it's not better than the reference solution it receives a negative symbol and if the concept and the reference solution is equal it receives a zero symbol. The symbols could thereafter be transferred to a quantified number according to the following:

- Positive symbol (+) is transferred to +1
- Zero symbol (0) is transferred to 0.
- Negative symbol (-) is transferred to -1.

If the result from each cell is summarized a result for that specific concept is found. If the result is negative the concept is inferior to the reference solution and if the result is positive the concept is better than the reference solution. Once all solution has been evaluated the concepts which has a lower result than zero could be eliminated which indicates that the concepts are not better than the reference solution. [3, p.184-186] Example of a relative decision matrix by the Pugh method is illustrated in figure 7.

Criterium	Concepts				
	1 [Ref]	2	3	4	5
Desire A		0	+	0	-
Desire B		+	+	+	+
Desire C		0	0	-	-
Requirement D		0	-	0	0
Desire F		-	+	-	-
Sum +		1	3	1	1
Sum 0		3	1	2	1
Sum -		1	1	2	3
Net worth	0	0	2	-1	-2
Ranking	2	2	1	4	5
Further development	Yes	Yes	Yes	No	No

Figure 7, example of a Pugh relative decision matrix.
Recreated from [3].

Kesselring

The inputs to the Kesselring matrix are both evaluated criterions and their weights, which both comes from the requirement specification. In the matrix the concepts are rated on how well they meet the criterions on a scale one to three, where three is a total fulfillment and one is not fulfilled. The rating (R) is to be multiplied with the criterions weight (W), which gives a quantified result (W x R). The results for each criterion are summarized to a total score for the concept which could be compared to an ideal solution or to other concepts. [3, p.189-190] Figure 8 shows a typical Kesselring matrix with weight, rating and quantified results.

Kesselring evaluation

Issued by: Date:	Kongsberg Maritime		Ideal			Concept 1			Concept 2			Concept 3			Concept 4		
Hampus Vinblad	File: Concept selection Kesselring		Description of concept 1			Description of concept 2			Description of concept 3			Description of concept 4			Description of concept 5		
Criteria:	Target	Weight (W) 1....... 5	Rating (R) 1 3	W x R	Comment	Rating (R) 1 3	W x R	Comment	Rating (R) 1 3	W x R	Comment	Rating (R) 1 3	W x R	Comment	Rating (R) 1 3	W x R	Comment
Criteria 1	15	5	3	15			0			0			0			0	
Criteria 2	15	5	3	15			0			0			0			0	
Criteria 3	6	2	3	6			0			0			0			0	
Criteria 4	12	4	3	12			0			0			0			0	
Criteria 5	9	3	3	9			0			0			0			0	
Criteria 6	15	5	3	15			0			0			0			0	
Criteria 7	15	5	3	15			0			0			0			0	
Criteria 8	15	5	3	15			0			0			0			0	
Criteria 9	15	5	3	15			0			0			0			0	
Criteria 10	12	4	3	12			0			0			0			0	
Criteria 11	12	4	3	12			0			0			0			0	
Criteria 12	15	5	3	15			0			0			0			0	
	156			156	Good Bad No changed		0	Good Bad No changed		0	Good Bad No changed		0	Good Bad No changed		0	Good Bad No changed
				100,0%	% of full		0,0%	% of full		0,0%	% of full		0,0%	% of full		0,0%	% of full

Figure 8, typical Kesselring matrix for concept selection.
Inspiration taken from [3].

2.4 Sustainability

Sustainable development has in the recent years become more important. The term sustainability is quite complex and could be simplified by the thought of leaving the world a better place than it was yesterday. The term could also be divided further into three aspects known as the triple Ps. The three aspect is people, planet and profit. All of the aspects should be considered during sustainable development. [4] A so-called SWOT analyse was performed to detect strengths, weaknesses, opportunities and threats to the product that is being developed. The attributes were connected to the three P's of sustainable development, which forms table 2.

Table 2, overview of the SWOT analyse.

	People	**Planet**	**Profit**
Strength	Increased personal safety.	Reduced risk of contaminations into the sea.	Reduced risk for an expensive breakdown.
Weaknesses	Over believing in the system.	Increased need of material.	System price.
Opportunities	Increased reliability and decreased transportation prices.	Functional failure could be avoided.	Bigger understanding of the ship.
Threats	The feeling of being watched with a monitoring system.	The product is non-sustainable.	The product becomes too expensive.

People

A CM-system is designed to indicate a potential functional failure before it occurs which is a strength that enables an increased personal safety for the passengers and the crew on the ship. The system is however a complement and shall not be used as a substitute to all other service and overhauling events that are supposed to be done. If the system is seen as a substitute, it could become a weakness. If the system is used correctly, it could indicate a risk of a potential functional failure and if correct actions are taken, the failure could be repaired before it damages other components. This fact could be seen as an opportunity as it could lead to an increased reliability which in the long run could decrease ticket and transportation prices. The CM-system could potentially identify that a human mistake has occurred which could have devastating individual effects on the person who made the mistake. It could lead to a situation where the owner of the ship keeps one person responsible for a potential functional failure. The CM-system owner needs to keep this in mind when the data is analyzed and the failure mechanism is to be presented to the owner of the ship.

Planet

Many components included in the Waterjet system are located under the sea level which makes it difficult for the ship crew to identify if any part of the system is leaking oil into the sea. The CM-system is therefore considered as a strength with the planet in mind, as it could identify such events. Installation of a CM-system requires additional components and could therefore be seen as a weakness from a planet perspective. More components simply increase the ship CO2 footprint. Even though the footprint might be increased by implementing a CM-system, in the long run it could be seen as an opportunity where the system decreases the overall CO2 footprint, due to the fact that a system could lead to preventing a functional failure where several components break down. The threat of the system is that implementation of the system has a higher CO2 footprint than a potential functional failure. This means that if a potential functional failure has the same impact on the environment as implementation of a new system, it does not make any sense to install the system from a planet point of view.

Profit

With an economical perspective there are massive advantages with a CM-system. A breakdown could not only cause substantial expenses to the actual components it could also cause significant expenses in delays, reschedules and missed departures. Except from direct expenses a breakdown could also lead to indirect expenses in terms of a decrease in the shipping company's reputation. The weaknesses that were identified from an economical point of view is that the CM-system becomes too expensive. The price of the CM-system should not exceed the price of a functional failure, if so, the customer might not see any advantages of buying the product which could also be seen as a threat to the product. The CM-system could aid the shipowner to understand why a failure occurs. If the failure were to be caused by incorrect or aggressive usage, the shipowner could take suitable actions to improve the ship reliability. The system also allows the CM-system owner to understand their product better and to develop components that receives an even higher reliability in the future.

Conclusions

There are a few aspects which should have a high priority during the product development. The first aspect is that the system shall not be more expensive than the components that it is designed to protect. If the system becomes more expensive than the system its designed to monitor it could be difficult to sell the system. The second aspect is that the system has a higher environmental impact than the system it is supposed to protect.

2.5 Literature study Equipment Health Monitoring

Condition Monitoring (CM) or also known as Equipment Health Monitoring (EHM) is a system which collects electrical signals and translates it to quantitative data. CM-systems are used widely around the world today both in transportation industries, power plant industries and in manufacturing industries.

2.5.1 Theory of Mechanical Failure

Equipment failure is a condition where the equipment could not meet its intended objective. Failure could be caused by several factors: [5, p.24]

- Design error.
- Faulty material.
- Improper manufacturing or construction.
- Incorrect installation.
- Inappropriate operation procedures.
- Insufficient maintenance.
- Maintenance inaccuracies.

Failure rate

Failure rate is defined as a frequency with which a developed system or component reaches functional failure, this could also be explained in failure per unit of time. It could be difficult to determine the time until failure occurs as it is depending on differences in the environment of the components. Therefore, it is based on probabilities and the most common probability model is the so-called *Conditional Probability failure rate* (λ) which is derived from the failure distribution model. It is based on the probability that a failure occurs during the next instant of time. The model could be interpreted into a graph where the horizontal axis represents the time (t) and the vertical axis represents the conditional failure rate as a function of time, $\lambda(t)$. [5, p.24-25]

Furthermore, it is important to understand that failures could be divided into three different failure modes:

- Wear-in failure – Often related to manufacturing defects and installation/maintenance/startup errors.
- Random failure – Could be caused by human errors et cetera and the failure is not time depending.
- Wear-out failure – Most often related to equipment end of life issues.

Failure pattern

The failure modes have different kind of failure patterns. Failure rates are traditionally used to determine when maintenance is supposed to be done on the equipment, but it could also be used when data from a CM-system is to be evaluated. For example, vibrations in a shaft might cause a bearing to functional failure and if vibration data were available to investigate further, it could be determined whether the functional failure was caused by wear-in failure, random failure or wear-out failure. This information is critical when determine a suitable approach for handling the failure mode and it is necessary to understand both failure rates and failure characteristics. The knowledge is essential to develop and improve the equipment's reliability. An overview of the failure characteristics is represented in figure 9. [5, p.25-27]

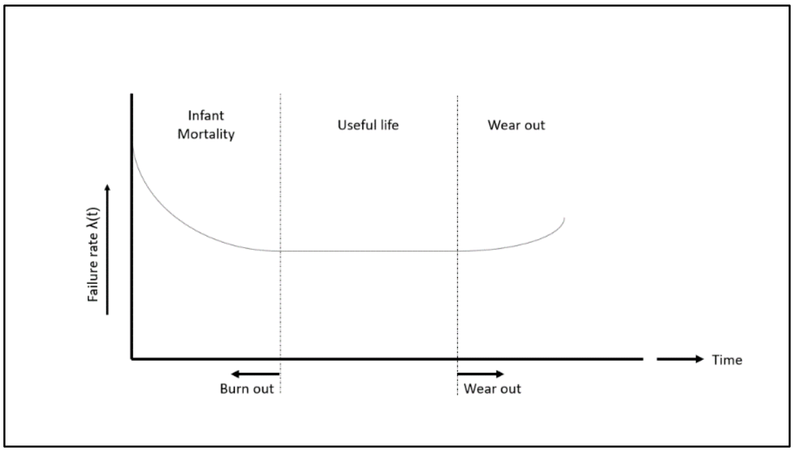

Figure 9, Overview of failure characteristics.
Figure recreated from figure 1 [5, p.27].

Wear in failure

A wear-in failure starts with a high probability of failure where the probability of failure decreases over time until it reaches a constant failure rate. An example of the failure pattern could be seen in figure 10. [5, p.26]

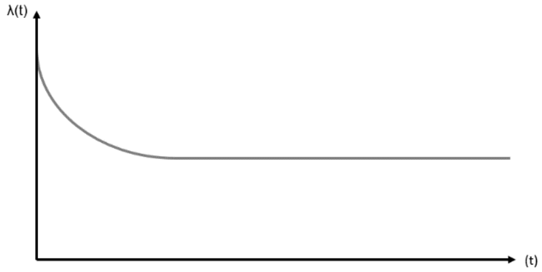

Figure 10, example of a wear-in failure pattern.
Figure recreated from table 1, p.26 [5].

Random failure

Random failures are not time dependent which means that the probability remains the same during the whole period of time. An example of a random failure could be seen in figure 11. [5, p.26]

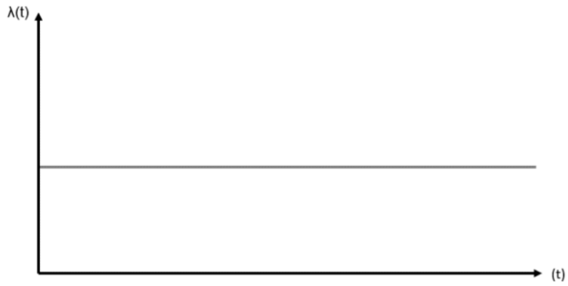

Figure 11, example of a random failure pattern.
Figure recreated from table 1, p.26 [5].

Wear-out failure

In a wear-out failure pattern, the conditional probability failure rate remains the same until the end of the product life, where the probability of a failure increases dramatically. An example graph is provided in figure 12. [5, p.26]

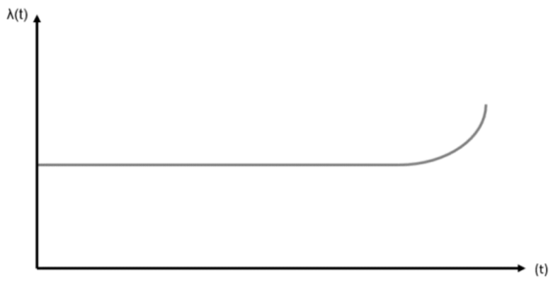

Figure 12, example of a wear-out failure pattern.
Figure recreated from table 1, p.26 [5].

Potential failure diagram (P-F)

Almost every time a failure or a functional failure occurs, it could have been avoided by performing a specific measurement for that specific condition. The measurements that could be performed within condition monitoring could be categorized as following: [5, p.31]

- Temperature measurements.
- Dynamic monitoring.
- Oil analysis.
- Corrosion monitoring.
- Nondestructive testing.
- Electrical testing.
- Observation and surveillance.

This means that it is important to use the correct measurement technique depending on which failure the system is designed to prevent. If the system is designed to prevent a bearing failure it could be of interest to investigate the lubrication oil quality, vibrations or rotational speed etc. Once the measurements are selected it is of importance to choose within which signal value the system shall normally perform and which value the system shall indicate a fault.

With this information, establishment of a so-called P-F diagram could be accomplished. P-F diagram is a diagram with time on the horizontal axis, equipment condition on the vertical axis and a line which indicates the condition per time unit. If no faulty condition were to be found, the diagram would only show a straight line with a constant condition but if a fault is present the line would first start to derive from its straight line where the failure occurs and the line would form an exponential function where the condition rapidly gets worse until functional failure occurs. At the line, three points could be added, one point where the failure begins, one point (P) where the failure could be detected and one point where the failure caused a functional failure (F). The interval between the point where the failure was able to be detected (P) and the point where functional failure occurred (F) is called the P-F interval. A so-called P-F diagram is illustrated in figure 13. [5, p.30]

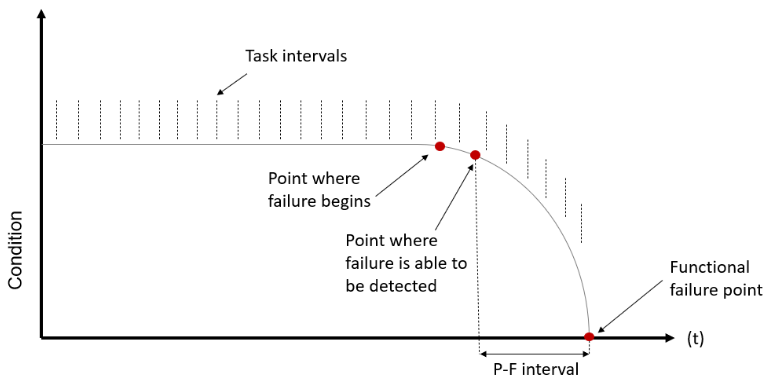

Figure 13, Illustration of a P-F diagram.
Figure recreated from figure 1, p.30 [5].

Monitoring task intervals

It is important to keep the P-F interval in mind when deciding the so-called task interval. The task interval is the time between the measurements and if the task interval were to have a longer interval than the P-F interval it could lead to a situation where the system never detected the failure. In general, the task interval should be set to maximum half of the P-F interval to ensure that the failure always becomes detected before it turns to functional failure. In the history it was of great importance to not use to much data as the memory cards was relatively small but with recent improvements within the tech industry the task intervals could be reduced to get more data, hence, more accurate investigations. The task interval should also be reduced for the following conditions: [5, p.32]

- If there is low confident in the expected P-F interval.
- If the failure mode has a higher risk.
- If the time interval is too small to perform corrective actions.

Measuring parameters

Parameters are defined as a physical phenomenon that are of special interest for that specific application. Parameter could for example be temperature, flow velocity, pressure or speed to mention a few. The parameter could be grouped into two different categories: [5, p.28]

- *Condition monitoring tasks*: Parameters that increases or decreases their value at the point where a failure begins. Example: Vibration levels or oil quality in a monitoring system for a bearing.
- *Surveillance tasks:* Parameters that does not react when a failure begins but could be convenience to review for understanding the failure mechanism. Example: Rotations speeds and torque which does not cause the failure and where the failure could not have been foreseen.

Task efficiency

To develop an effective equipment health monitoring system, the following factors should be considered: [5, p.31-32]

- There should be some sort of measurable parameter that could detect that a failure is about to occur. More specific, the beginning of a failure must be detectable.
- The P-F interval should be carefully chosen so that actions aren’t taken prematurely nor too late.
- Practical intervals should be selected, in which monitoring tasks could be performed.
- The system should have appropriate warnings so that proper actions to prevent functional failure could be accomplished.
- The task intervals should be performed so that the probability of a failure is on an acceptable risk level.
- The cost of the system should not be higher than the cost of the equipment it’s supposed to protect.

Parameter threshold

A threshold is defined as an amount, level or limit. Once the threshold is reached, something is supposed to happen or change elsewhere. In this specific application a threshold is used on the parameter and once the threshold is reached the system shall set an alert or a fault message. The parameter threshold could either be an upper limit, a lower limit or a combination of them both. The point where a failure could be detected in a P-F diagram is a so-called threshold. Upper parameter thresholds should be used when a fault increases the value of the measured parameter and lower parameter thresholds should be used when a fault instead decreases the value. A combination of those could be used when the used parameter neither should increase or decrease their value. Figures 14, 15 and 16 shows examples of different thresholds.

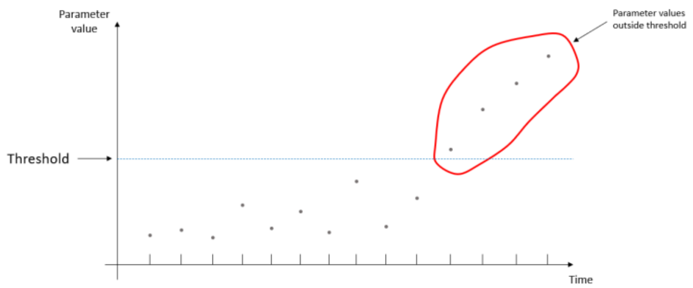

Figure 14, example of an upper threshold

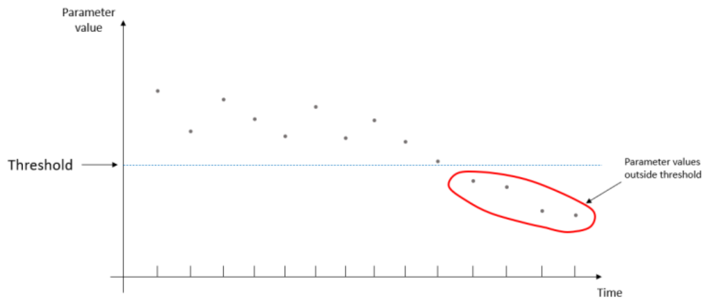

Figure 15, example of a lower threshold

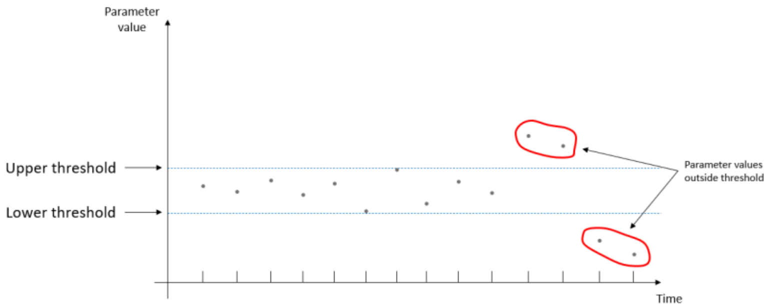

Figure 16, example of a combination of upper and lower threshold.

2.5.2 Theory of Condition Monitoring

The fundamental process though of conditional monitoring could be compared to the widely known PDCA-cycle. The process of conditional monitoring also has a four-step iterative process which is illustrated in figure 17.

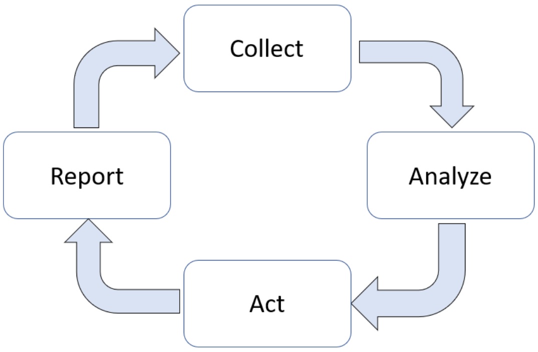

Figure 17, conditional monitoring process.
Recreated from [5].

Collection of data

The main function of a condition monitoring system is to monitor interesting physical parameters. The physical parameters could be pressure, flow, speed, forces acceleration or any other relevant units. The parameters could be translated to electrical signals with so-called sensors. Different sensors use different measuring techniques but their function remains the same, translate a physical phenomenon to a corresponded electrical signal. The electrical signals are forwarded to an electrical control module where the signal is converted to data. The electrical signal could also be used to set a visual alert to the user or to start other systems.

Analyze

During the conversion of the electrical signal to data the control module saves the signal together with a timestamp in a so-called datalogger. The datalogger is basically just a memory card where the data afterwards could be extracted either over the air or by inserting an ethernet cable. Since all the saved signals values now has a timestamp, the data could be sorted and interpreted into a graph with time on the x-axis and signal value at the y-axis. Figure 18 shows an example of how the data could be visualized. If more parameters were to be measured it increases the understanding of the failure mechanism and the root cause of the failure could be more precisely pin pointed.

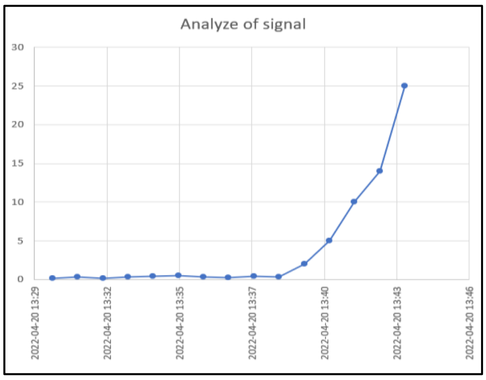

Figure 18, example of data visualization.

Act

An alert is a visual message to the user that a specific action is needed. The alert is based on thresholds which is a value that the signal shall not exceed. If the signal exceeds the value an alert is to be set to the user. Alerts could, but must not, be divided into low and high alerts. A low alert recommends the user to take certain actions while a high alert orders the user to take certain action. Precise alerts and data could help the product owner or the client to determine which action or repair that needs to be performed without physically inspect the equipment which both reduces the repair time and the waiting time for parts to arrive.

Report

Furthermore the condition monitoring system data could be used to create reports which could indicate wear which could assist the service team onboard to repair components at an early stage or during dry-docking. Once the required repair has been performed the process starts over again. [5]

2.5.3 Failure causes for waterjet applications

There are several potential causes which could lead to a function failure of the shaft bearing arrangements and the hydraulic system. A lubricated roller bearing failure could appear due to following factors:

- Metallurgical factors and manufacture.
- Poor assembly, misalignment, dirt in lubrication.
- Fatigue, cracks and pits.
- Fretting and false brineling.
- Corrosion, contact staining, general attacks.
- Inadequate lubrication.
- Electrical discharge.
- Combination of the above.

Most of the failure causes are caused or worsened by either particle or water contaminations. Depending on failure cause the failure pattern might look different. For example, an incorrect alignment might have a high failure rate in the beginning which will flatten out once the equipment has been worn in. Another example is corrosion caused by water particles in the hydraulic oil which has a low probability failure rate in the beginning but where the probability failure rate increases with time, so-called wear out failure. [6, p.150]

2.5.4 Benchmarking of Condition Monitoring Systems

Condition monitoring has in recent years become an important system within certain industries. Even though the usage of condition monitoring is limited within the shipping industry there are many companies who is specialized in development of condition monitoring systems for wind turbines for example and the basic fundamentals are the same. Both industries have an interest of measure the wear of rotating equipment from a long distance in order to reduce the service costs. Many of the large hydraulic companies have developed their own condition monitoring system designed to evaluate the hydraulic oil which was also benchmarked. Even though several interesting parameters was identified in the project specification from Kongsberg, a so-called benchmarking process was performed in order to confirm and potentially identify more parameters of interest. During the benchmarking process it was found that the following parameters are usually measured in a condition monitoring system:

- Solid particles in hydraulic oil [p/ml].
- Humidity in hydraulic oil [PPM].
- Vibration [Hz].
- Load (Torque on the shaft) [Nm].
- Bearing lubrication temperature [°C].
- Lubrication fluid flow [l/min].
- Rotation speed of the shaft [RPM].

2.5.5 Literature study on recommended Parameters

2.5.5.1 Solid particle contamination parameter

A large portion of all hydraulic system breakdowns are caused by different kind of contaminations. [6] The contaminations could be divided into two groups. The first group is the solid particle contamination. This specific parameter will be used to measure solid particle contaminations. [7] The most common solid particle contaminations are metal particles, seal particles or dust particles from manufacturing. Their presence could be caused by following external or internal reasons: [6, 7]

- Filling with exposed hydraulic oil. *(External reason).*
- Insufficient cleaning of the system after manufacturing. *(External reason).*
- Defective breathing filters. *(External reason).*
- Defective seals and scrapers. *(External reason).*
- Carelessness during service. *(External reason).*
- Corrosion due to water ingress. *(Internal reason).*
- Cavitation damages due to water ingress. *(Internal reason).*
- Worn components. *(Internal reason).*
- Fatigue damages. *(Internal reason).*

Once the particles are introduced in the system, they generate damages to all components within the hydraulic system which reduces the hydraulic systems reliability and could eventually cause a functional failure. The sizes of the particles could be so small that they can’t be visually seen with an eye. The quantity of particles is in a way proportional to the conditional probability failure rate.[6] The more particles present in the hydraulic system, the more likely it is for the system to reach a functional failure. The quantity of particles is therefore a valid and measurable parameter to ensure that functional failure does not occur. Since the parameter could be used to identify a potential functional failure, it should be defined as a condition monitoring task parameter according to ***Subsection 2.4.6.*** The cleanliness of hydraulic oil is generally measured according to ISO 4406:1999. The standard is used to quantify particles into three size categories, particles which is 4µm or larger, 6µm or larger and 14µm and larger. The cleanliness code could for example be 19/17/15, where the numbers correspond to a specific range presented in table 3 and the positions of the numbers is specified in figure 19. [8]

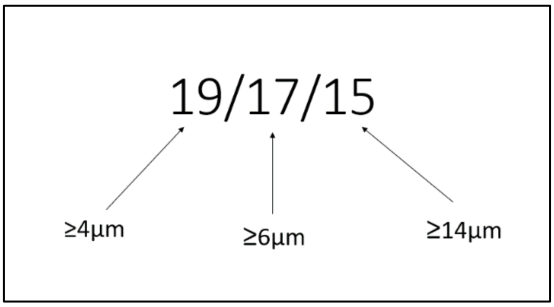

Figure 19, ISO-code example.

Table 3, ISO 4406:1999 cleanliness table.

More than [p/ml]	Up to and including [p/ml]	ISO Code
80.000	160.000	24
40.000	80.000	23
20.000	40.000	22
10.000	20.000	21
5.000	10.000	20
2.500	5.000	19
1.300	2.500	18
640	1.300	17
320	640	16
160	320	15
80	160	14
40	80	13
20	40	12
10	20	11
5	10	10
2.5	5	9
1.3	2.5	8

2.5.5.2 Humidity contamination parameter

The other group of contaminations in a hydraulic system are the humidity contaminations. Humidity contaminations could consist of any kind of liquid, but in this application water presence is especially interesting. Water presence in the hydraulic system could cause corrosion, cavitation, oxidation, viscosity changes and other damages to the hydraulic system. Presence of water inside the hydraulic system could be caused by following reasons: [9]

- The system has been internally cleaned with pressurized water.
- Leaking components.
- Defective seals.
- Filling with oil that has been exposed to water.

The amount of water presence in the hydraulic oil is proportional to the conditional probability failure rate. Which means that, the more amount of water that is present in the system the more likely it is for the system to reach functional failure. This fact enables the parameter to be seen as a condition monitoring parameter which could be measured and where thresholds could be set. There are generally two different methods to measure humidity in oil. As per today, Kongsberg Maritime uses the so-called absolute humidity [PPM] to determine if the hydraulic oil is contaminated by water. To receive absolute humidity, the so-called Karl Fischer method is normally used in a controlled laboratory with a fixed oil temperature. The absolute humidity could be calculated by multiplying the relative humidity (φ) by the saturation limit of the hydraulic oil ($\rho_{w,max}$) and dividing the values by 100%, which gives equation 1. Relative humidity (φ) is a percentual ratio between the actual water contained in the oil and the maximum possible amount of dissolved water at the saturation limit, which is shown in equation 2. Somewhat simplified, the saturation limit ($\rho_{w,max}$) is the amount of water that specific oil could absorb before the water creates emulsions or becomes free water. Due to the fact that hydraulic oils could absorb more water with increasing temperature, the saturation limit becomes a variable which is depending on the oil temperature. The saturation limit also variates with the oil type and the oil age. For example, if the working temperature of the hydraulic system is 50°C the saturation limit will be higher than it was during start-up, hence, the oil will be able to absorb more water. If the oil instead is sent to a laboratory the measurement will be performed in 25°C and the saturation limit will become lower which will give a higher absolute humidity then it was in the actual system. Due to the complexity of measuring absolute humidity there are no methods available on the market which could measure the parameter on-line, instead oil samples need to be taken in the system and sent to a laboratory for review. However, there are on-line methods available to measure the parameter relative humidity which gives an output interval between 0-100%, where 100% indicates that the water is either free or that emulsions are present. Another available parameter is water activity which basically is relative humidity divided by 100. The difference is that relative humidity is in percent while water activity is not.

$$\textit{Equation 1:} \quad Absolute\ humidity\ [\rho_w] = \frac{\varphi \times \rho_{w,max}}{100\%}$$

$$\textit{Equation 2:} \quad Relative\ humidity\ [\varphi] = \frac{\rho_w}{\rho_{w,max}} \times 100\%$$

The absolute humidity is traditionally the more used parameter to measure the contamination of water in oils but measuring the relative humidity parameter gives a better picture of the oil condition, at least for on-line measurements. The relative humidity gives a firmer indication of the risk for free water in the system. Relative humidity is neither affected by fluctuation in the saturation limit which means that the output value could be trusted even if the temperature change or if the oil changes its physical behavior. Finally, the relative humidity parameter is also not affected by differences in saturation limits which could be caused by different oils. As mentioned, the parameter is measured within an interval between 0 to 100%. A value lower than 40% indicates that the hydraulic oil is not contaminated by water, a value between 40% to 60% indicates that the system could have a water ingress and a value above 60% indicates that the system has a water ingress which could damage the system and therefore action is required, a summarize could be found in table 4. [9]

Table 4, reference values for measure values.

0 – 40 % r.h.	No actions required (Oil is dry)
40 – 60 % r.h.	Control the oil and installation
60 – 100 % r.h.	Hydraulic system has water ingress, action needed.
General condition for reference values	Air temperature: 20-25°C Air humidity (approx.): 20-70% Oil temperature (approx.): 45°C

2.5.5.3 Vibration parameter

The parameter and the measurement are going to be used on locations where vibrations are known to appear, but the values are either unknown, uncertain or could be interfered by other vibrations which makes it inefficient to use as a condition monitoring task parameter. Therefore, it is classified as a surveillance task parameter which could aid to understand the failure mechanism. In the future, when data of the vibration levels and frequencies has been properly investigated and a failure pattern and behavior could be identified, the parameter could be changed to a condition monitoring task parameter [10, p.164]. The parameter is measured in either Hertz [Hz], mm/s or mm/s^2.

2.5.5.4 Torque parameter

The torque parameter is also classified as a surveillance task parameter and could be beneficial to have when analyzing the failure mechanism. The torque parameter could be interesting to investigate during a failure event as it could indicate how much load the ship was exposed to. The parameter is measured in Newton meters [Nm].

2.5.5.5 Hydraulic flow parameter

The parameter is of interest since a too low flow could cause inadequate lubrication to the bearings which could cause a functional fault. The hydraulic system is divided into a low-pressure system which is called the lubrication system and a high-pressure system. The lubrication system has two tasks, to lubricate the impeller bearing and the shaft bearing. If the flow would decrease for any reason, it would lead to a dried out bearing which will allow heat production that could lead to a bearing breakdown. The flow has a lower limit which it should not exceed, the parameter could therefore be seen as a condition monitoring parameter. The hydraulic flow is measured in liter per minute [l/min].

2.5.5.6 Rotation speed parameter

The rotation speed parameter is a so-called surveillance task parameter. The rotation speed is not going to indicate a functional failure, but a constant high rotation speed could have an impact on the failure, which could be of interest to understand the failure mechanism. The parameter could also be used to monitor how long time the ship has been operating and how many rotations the shaft have accomplished. The parameter is measured in rotations per minute [RPM]. [10, p.135]

2.5.6 Literature study on measurement methods

2.5.6.1 Solid particles contamination measuring methods

Ferromagnetic sensors

The ferromagnetic sensor is a so-called magnetic chip detector which attracts metal particles with an electromagnet. Once the particles are stuck on the sensor lens, the oscillating frequency change depending on the size of the particles. Once the measurement has been performed the electromagnetic is released which forces the particles to continue their path inside the hydraulic system. Since the sensor uses electromagnetics to collect the material, the method is not suitable for non-ferrous particles. [11]

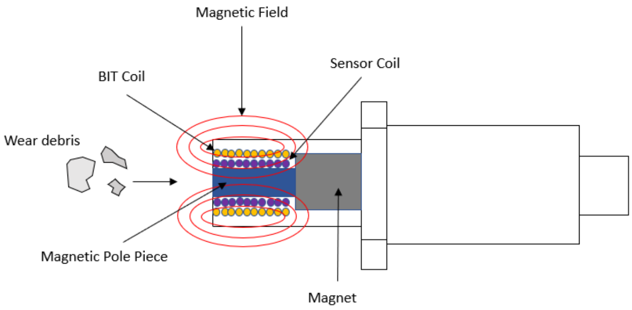

Figure 20, example of a typical Ferromagnetic sensor Recreated from [11].

Metal Debris Sensor

The metal debris sensor has an inlet and an outlet and could easily be mounted on a pipe, figure 21. It usually consists of a sensor head with two stimulus coils and one sensor coil which are wound around an isolated part of the pipe. When particles pass through the pipe, the field that has been created by the stimulus coils is disturbed and recorded by the sensor coils. The method has a low chance of false indications and could be used to identify both ferrous and non-ferrous particle sizes. [11,12]

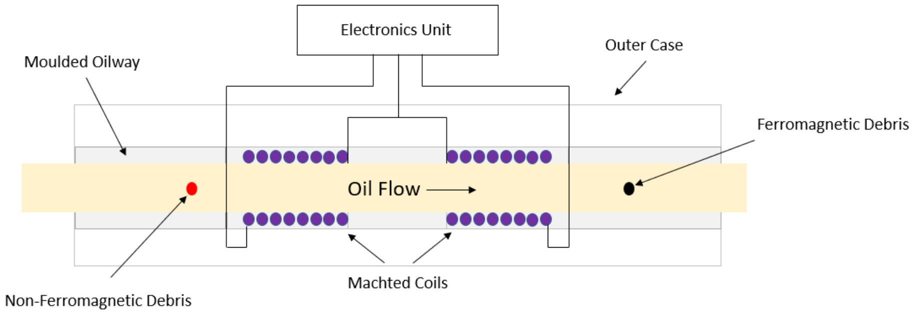

Figure 21, example of a typical Metal Debris sensor Recreated from [11].

Light scattering particle counter

This method is more advanced but could also be used for on-line measurements. The sensor could be mounted directly on hydraulic pipes. The method uses a laser light source and a photo diode, figure 22. If no particles pass the laser beam, all lights are being reflected to the photo diode but if particles pass the laser beam, the beam is going to be reflected and the photo diode could decide the size of the particle. The method has some weaknesses though. The method could react to water contamination, air bubbles and fluid opacities and could therefore result in inaccurate readings. The size determination is also influenced by which side of the particle the laser hits, if the short side of a particle is struck it could result in inaccurate readings. The method could not determine what chemical composition the particles have. [11,13]

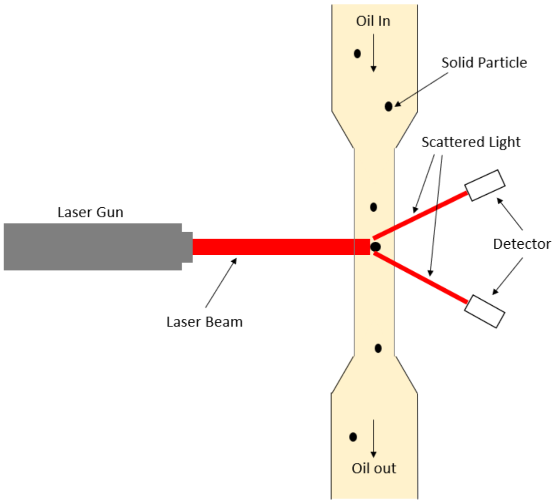

Figure 22, example of a typical Light scattering particle counter. Recreated from [11].

2.5.6.2 Humidity particle contamination measuring methods

Capacitive thin film sensor

The technology consists of functional thin films which is called layers. The thin-film polymer sensor absorbs and releases water when the surrounding moisture level in the hydraulic oil changes. The absorbing and desorbing of water molecules appear until a moisture equilibrium is reached between the polymer and the hydraulic oil. Changes in the moisture level of the hydraulic oil quickly changes the dielectric properties of the polymer film, which causes the capacitance of the sensor to change. The so-called upper layer of electrode prevents oil, additives and particles from penetrating through the polymer which allows the sensor to only measure water molecules which enables the functionality that the sensor is independent of the oil type. [14] The measurement method could be installed on-line and measures relative humidity in percent [%].

Different kind of light source and reflection sensors

There are a few different kind of measurement methods that are based on a light source and a photo diode technique which could identify water particles, but they also identify ferrous and non-ferrous materials. Because the method also includes solid particles their suitability could be questioned. [5]

2.5.6.3 Rotation speed measuring methods

Magnetic field sensors

Magnetic field sensors are sensors that detects presence of magnetic fields. By adding a so-called reluctor ring to the rotating shaft the sensor will react each time a tooth of the reluctor ring passes the sensor. The sensor output will become either a pulse signal or sinus signal. The faster the shaft rotates the shorter the time of the pulse or the wavelength will become. By analyzing the signal an output of the actual rotating speed could be determined. The most common magnetic field sensors are called hall sensors and inductive sensors.

Photoelectric sensors

Photoelectric sensors use a light transmitter and a receiver in combination with a reflector. The transmitter sends out a light which is reflected by the reflector and once the reflected light hits the receiver an electric current is allowed. The reflector is installed on the shaft which allows an electrical signal each revolution the shaft makes. The time between each signal could determine the rotational speed. If the reflector would pass the light once each second the rotational speed would be 60 rotations per minute.

2.5.6.4 Torque measuring methods

Strain gauge sensor

Torque is a measurement of an applied force ability to twist an object. In this specific case, the shaft and the impeller. Once the torque is applied to the shaft it will cause the shaft material to deform and slightly twist.

If a metal wire were to be stretched out the length would increase but since the volume of the wire is fixed the cross-section area would have to decrease the more the wire is stretched. A decrease in the cross-section affects the electrical resistance, this phenomenon is called the piezoresistive effect. A so-called strain gauge sensor applies the piezoresistive effect on a thin metal film and once the tension is added to the measured object the resistance increases. The resistance of the thin film is also affected by temperature changes which could be fixed by using a Wheatstone bridge. Wheatstone bridges are designed to determine an unknown resistance. The bridge consists of four resistors and one measuring device, as described in figure 23. If R_1 and R_3 has a known resistance, then the resistance of R_2 could be adjusted until the voltage on the bridge reaches zero voltage. Once an equilibrium has been reached, the unknown resistance of R_x could be determined by multiplying R_2 with the product of R_3 divided by R_1, see equation 3.

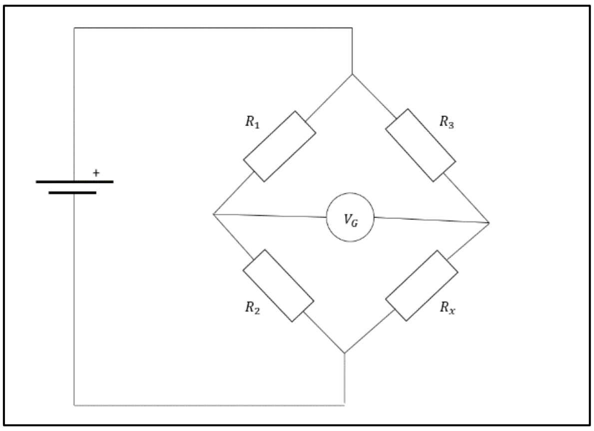

Figure 23, Wheatstone bridge circuit diagram.

Equation 3: $$R_x = R_2 \times \frac{R_3}{R_1}$$

In a strain gauge sensor, the Wheatstone bridge is not specifically used to determine unknown resistance, it is rather the imbalance and the voltage output that occurs in the bridge that are of interest. To measure torque in a shaft with this method, the resistors are placed at an angle of 45 degrees from the shaft axis as described in figure 24. If torque, which causes shear strain, is applied to the shaft, the arrangement described above will cause elongation in R_1 and R_3 and compression in R_2 and R_4. The elongation will cause increase in the resistance for resistors R_1 and R_3 and the compression will cause decrease in resistance for resistors R_2 and R_4. This results in an unbalanced Wheatstone bridge where the voltage output is proportional to the applied torque and could therefore be used to determine the shaft torque. [15, p.164; 16, p.98]

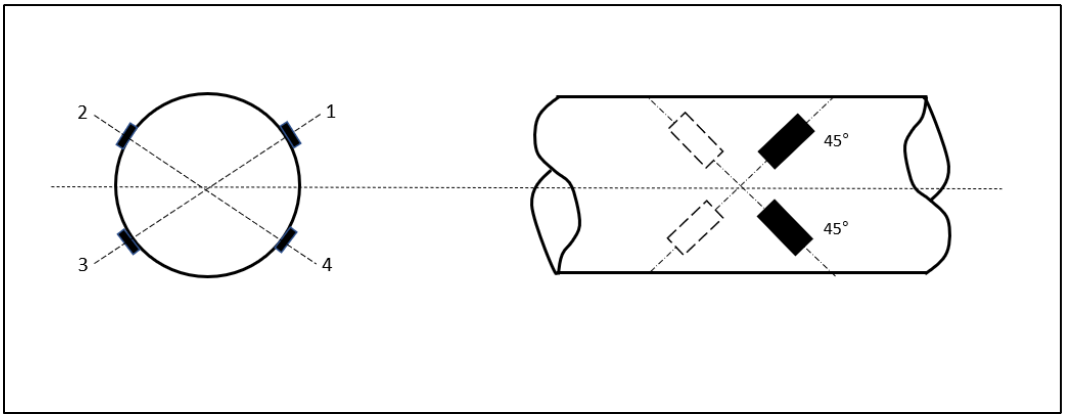

Figure 24, Strain gauge sensor installed on a shaft.
Figure recreated from [15, p.165].

Other options

There are a few other methods available on the market to measure torque, but they are either not designed for a rotational shaft or their accuracy are not good enough.

2.5.6.5 Vibration measuring methods

The most common method to measure vibrations are the accelerometer. The general principles of an accelerometer are fairly simple. The accelerometer consists of an enclosure which is fixed to the object where the acceleration or vibration might appear, a free mass and some kind of sensor which is measuring the displacement of the mass. Most of the accelerators are so-called three axis accelerometers. The three axis accelerometers are designed as system of three separated accelerometers which measures the acceleration in X, Y and Z direction of a cartesian coordinate system. The measurement methods which are normally used to determine the displacement of the free mass is MEMS Capacitive, piezoresistive and piezoelectric. [16, p.150]

MEMS Capacitive accelerometers

The principle for a one-dimension MEMS capacitive accelerometer is illustrated in figure 25. The mass is installed into the enclosure through springs and so-called anchor points. The mass has moving fingers installed on it while the enclosure has fixed fingers, this is called comb structure. When a vibration or acceleration of the mass appears the capacities between the fixed fingers and the moving fingers changes which could be used to determine and translate the acceleration to an electrical signal. Between every moving finger there is two fixed fingers which are supplied with different potential. The MEMS capacitive accelerometers are the cheapest of the three types described in this document and their accuracy is lower for high amplitudes and frequencies. [16, p.150-153]

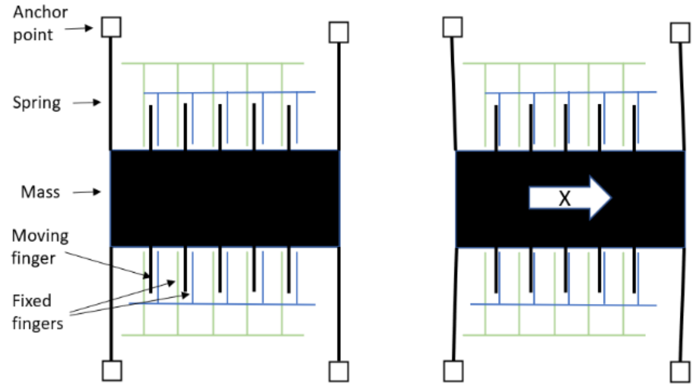

Figure 25, top view of a one-dimensional MEMS capacitive accelerometer. Recreated from [17, p.152]

Piezoresistive accelerometers

The piezoresistive accelerometer consists of a proof mass which is attached to the supporting frame with beams which is illustrated in figure 26. Once an acceleration appears, the mass will deflect due to its inertia and the supporting frame will remain rigid in its enclosure, which will cause the connecting beams to deform. The beam deformation could be measured using resistors, piezoresistive effect and a Wheatstone bridge. The measurement method has a wide measuring range but a low sensibility. [15, p.211]

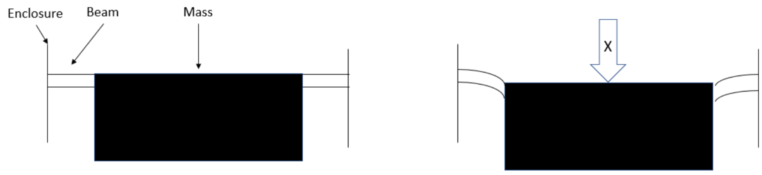

Figure 26, illustration of a piezoresistive accelerometer.

Piezoelectric accelerometers

The Piezoelectric accelerometer consists of an enclosure, a mass and a piezoelectric material which is normally called a crystal, see figure 27. When an acceleration appears, the mass and the enclosure want to separate from each other but is impeded by the piezoelectric material. This results in a situation where the piezoelectric material gets deformed which could be observed with a change of the electrostatic force or their voltage potential. The output voltage is fairly low why some sort of amplifier is needed. The method has a higher impedance and could be more difficult to produce than the other two alternatives. The piezoelectric accelerometers are highly sensitive and accurate and could measure high frequencies. [15, p.208]

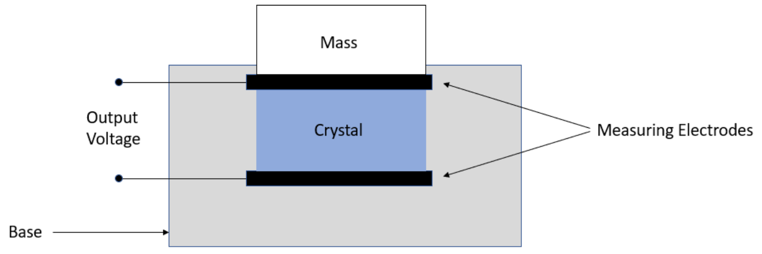

Figure 27, layout of a piezoelectric accelerometer.

Analyse methods

All vibration and acceleration sensors output signals are so-called alternating current (AC]. The reason for this is because they are able to sense a movement which is both positive and negative. All rotating parts has their own vibration signature which is created by the combined individual parts. The amplitude of the signature varies when the equipment experiences unusual behaviors, such as unbalance or abnormal bearing wear. Analyzing the vibration signals could generally be done in two different ways. The first method is analyzing the overall vibration of the machine by using the so-called time domain vibration analysis. The name comes from the analyze which is presented in a graph with time on the x-axis and amplitude of the movement in the y-axis. The second method isolates each amplitude to a specific frequency. This method is called frequency domain vibration analysis. Time domain therefore monitors signal amplitude over time while frequency domain monitors signal amplitude by frequency which could be visualized in figure 28. Both methods could be used in condition monitoring but their strengths and weaknesses are different. The strengths of time domain analysis are their simplicity and low price and the weaknesses is that time domain analysis detects a fault later and could not pin-point the vibration as good as a frequency domain analysis could. [17,18]

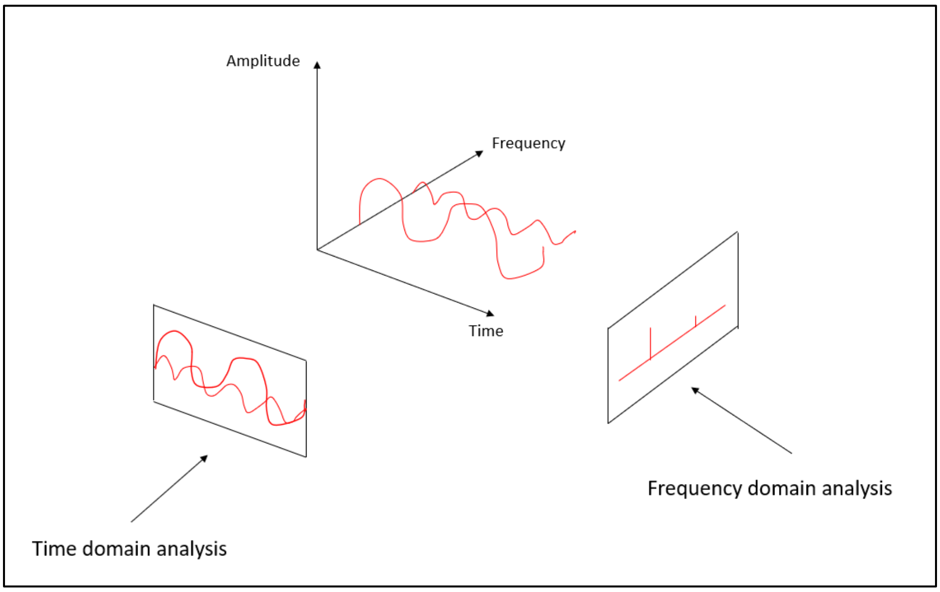

Figure 28, visualization of the different perspectives of time domain and frequency domain analysis.

Root mean square (RMS) value of velocity

One of the most important values to monitor when it comes to vibration is the so-called root mean square (RMS) value of velocity. The importance comes from the fact that the RMS value is directly related to the energy content of the vibration profile and the destructive capability of the vibration. The RMS value also take the time history in to account since it is a mean value of the vibration peaks. The RMS velocity is measured in mm/s and is further illustrated in figure 29. [18]

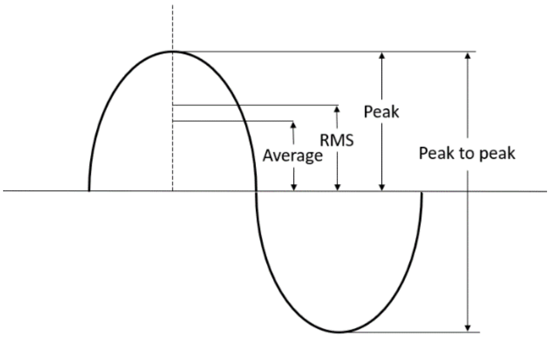

Figure 29, illustration of the time domain sinus wave.

ISO 10816-3- Mechanical vibration

The ISO 10816 standard is used for mechanical vibrations, more specific measurement and evaluation of machine vibration. In part 3 of the standard, figure 30 is presented which recommends that a vibration velocity (RMS) of 28mm/s is unacceptable for a so-called class 4 machine type. [19]

<table>
<tr><td colspan="3">Machines</td><td colspan="2">Frequency range for v-RMS calculation</td><td colspan="2">Technical standard</td></tr>
<tr><td colspan="3">Rotating standard machines: Motors, fans, shafts, generators, pumps</td><td colspan="2">2-1000 Hz (for 600 > n > 120)
10-1000 Hz (for n > 600)</td><td colspan="2">ISO 10816-3</td></tr>
<tr><td colspan="7">Vibration level reference guide (Based on ISO 10816-3)</td></tr>
<tr><td colspan="3">Machine type:</td><td>Class 1</td><td>Class 2</td><td>Class 3</td><td>Class 4</td></tr>
<tr><td colspan="2">in/s</td><td>mm/s</td><td>Small Machines (20hp)</td><td>Medium Machines (100hp)</td><td>Large machines rigid foundation</td><td>Large machines soft foundation</td></tr>
<tr><td rowspan="12">Vibration velocity (RMS)</td><td>0,01</td><td>0,28</td><td rowspan="3">Good</td><td rowspan="4">Good</td><td rowspan="5">Good</td><td rowspan="6">Good</td></tr>
<tr><td>0,02</td><td>0,45</td></tr>
<tr><td>0,03</td><td>0,71</td></tr>
<tr><td>0,04</td><td>1,12</td><td rowspan="2">Satisfactory</td></tr>
<tr><td>0,07</td><td>1,8</td><td rowspan="2">Satisfactory</td></tr>
<tr><td>0,11</td><td>2,8</td><td rowspan="2">Warning</td><td rowspan="2">Satisfactory</td></tr>
<tr><td>0,18</td><td>4,5</td><td rowspan="2">Warning</td><td rowspan="2">Satisfactory</td></tr>
<tr><td>0,28</td><td>7,1</td><td rowspan="5">Unacceptable</td><td rowspan="2">Warning</td></tr>
<tr><td>0,44</td><td>11,2</td><td rowspan="4">Unacceptable</td><td rowspan="2">Warning</td></tr>
<tr><td>0,7</td><td>18</td><td rowspan="3">Unacceptable</td></tr>
<tr><td>1,1</td><td>28</td><td rowspan="2">Unacceptable</td></tr>
<tr><td>1,8</td><td>45</td></tr>
</table>

Figure 30, ISO 10816-3 chart of acceptable vibration velocities (RMS). Recreated from [19]

2.5.6.5 Hydraulic flow measurement methods

Magnetic-inductive sensors

The magnetic-inductive flow sensor is based on Faradays law. Faradays law states that the voltage induced in a conductor which moves through a magnetic field is proportional to the velocity of that conductor. Since the area of the sensor is known the flow could be decided by multiplying the area with the velocity. [20]

Vortex flow sensor

The vortex flow meter consists of a flow sensor which could sense pressure variations due to a vortex-shedding phenomenon which is built-up by adding a so-called bluff that creates a passage. The pressure variation is normally measured with either piezoelectric or capacitive type sensors. [21]

Mechanical flow sensor

There are a few different kind of mechanical flow sensors but the most common is the spring-loaded piston. If no flow is present, the piston remains resting and once flow is introduced the piston starts to move due to the forces that is acting on it. The movement of the piston could be measured and converted to an electrical signal proportional to the flow.

2.6 Protection cabinet for control module

The control module that will be used to process the electrical signals has an IP20 protection classification which is less than the required IP44 protection classification needed for machinery spaces according to the classification societies. Therefore, the control module needs to be built into a cabinet which is protecting the device from contaminations. The first option is to design a new cabinet which will require extensive work to receive a classification of at least IP44 class and the second option is to buy an already classified cabinet and re-build it for the control module.

3 Implementation

3.1 GANTT chart and WBS

3.1.1 GANTT chart

The GANTT chart for the project was created in *Microsoft Excel*. The project was divided into distinct phases with input from hard deadlines within the course, input from the WBS and with a double diamond approach. The phases were the following:

- Planning.
- Research.
- Requirement specification.
- Report 1.
- Concept generation.
- Concept selection.
- Concept design.
- Report 2.
- Report 3.

Each phase was also divided into separated GANTT charts with more detailed information on which tasks that needed to be performed during that phase. The GANTT chart could be found in figure 31.

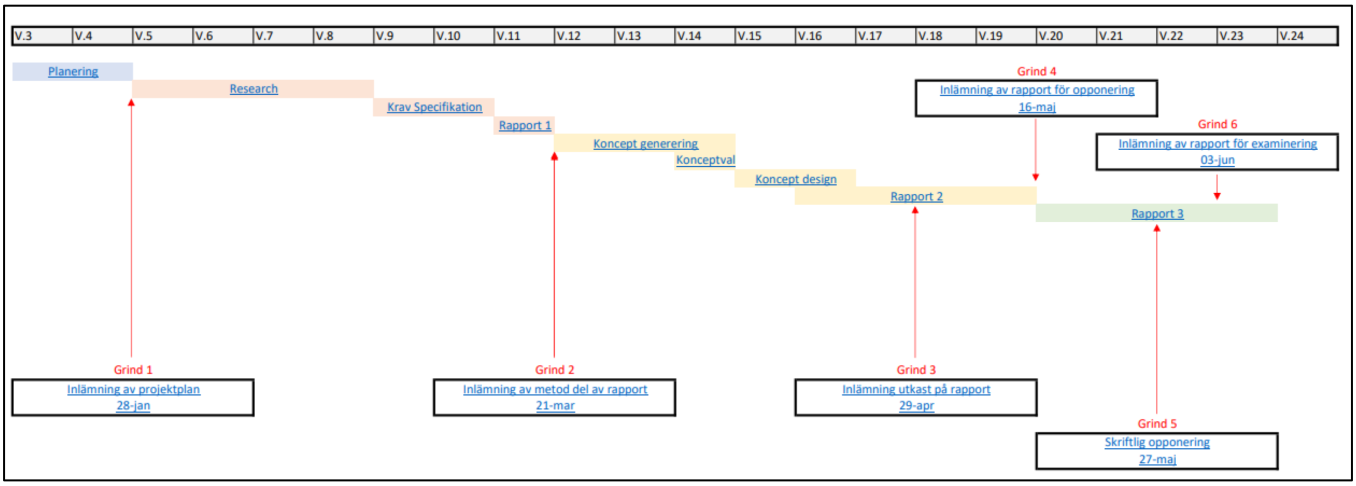

Figure 31, overview of the GANTT chart.

3.1.2 Work breakdown structure (WBS)

A CM-system could be roughly broken down into three layers:

- The first layer is the collection of sensors and transducers signals. **Sensors and transducer signals.**
- The second layer is receiving and manipulating the data. **Data acquisition.**
- The third layer where the data is analyzed and visualized. **Data review and process.**

This work will mainly focus on the sensor and transducer signal layer but since the task includes development of a cabinet for the control box also the Data acquisition layer will be fairly affected. The sensor and transducer signals layer could be further divided into subcategories which are the following:

- Solid particle measurements.
- Humidity measurements.
- Rotations speed measurements.
- Torque measurements.
- Vibration measurements.
- Flow measurements.

Furthermore, the subcategories have objectives that must be considered during the development. The project specification requires that the sensors should be compatible with the existing CanMan Touch control system, that the development should comply with the rules from the classification society, that IP-classes and placements should be considered.

The control box category could also be divided into subcategories but for this thesis only one of the subcategories are of interest. The subcategory of interest is the protection cabinet for the control box. The protection cabinet also has objectives that needs to comply with rules from the classification society combined with the demands of IP-class and component placement.

An overview of the work breakdown structure has been created to further visualize the system in figure 32.

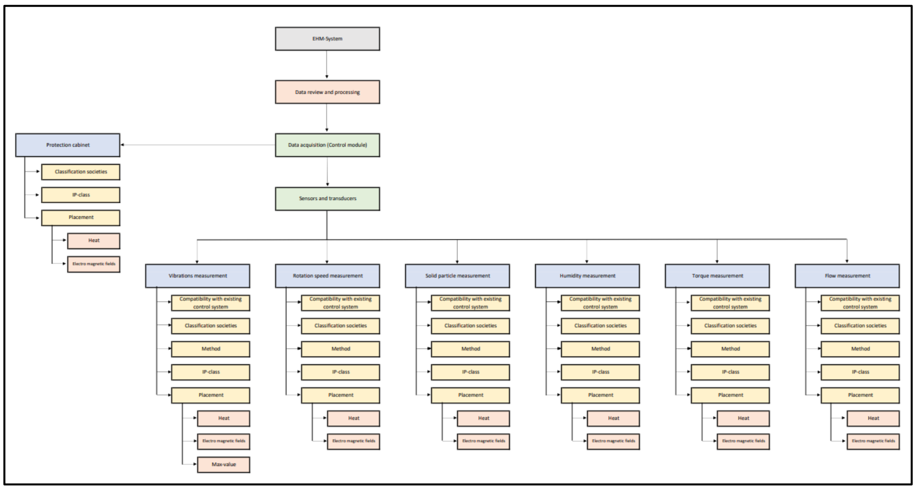

Figure 32, overview of the WBS.

3.2 Requirement & Functional specification

3.2.1 Requirement specification

One requirement specification was created for the cabinet and one requirement specification was created for all sensors. Most of the requirements on the sensors are set by rules from the classification society which are the same for all sensors but the sensors also have requirements and desires which is specific to that sensor. In order to avoid creating requirement specification to each sensor the requirement specification was divided into the following criterion categories:

1. Construction requirements from classification.
2. Placement requirements from classification.
3. Environmental requirements from classification.
4. Electrical requirements from classification.
5. General Requirements and desires from Kongsberg Maritime.
6. Requirements and desires specific for solid particle sensor.
7. Requirements and desires specific for humidity sensor.
8. Requirements and desires specific for rotations speed sensor.
9. Requirements and desires specific for torque sensor.
10. Requirements and desires specific for vibration sensor.
11. Requirements and desires specific for flow sensor.

The input to the requirement specification came from the following sources:

- Rules from the classification societies. (DNV, BV and ABS)
- Parameter values from Kongsberg internal documents.
- Input and meetings with Kongsberg representatives.
- Functional specification.

The requirement specifications as whole could be found in *Appendix A.*

3.2.2 Functional specification

The main function of a Condition monitoring system is to examine physical phenomenon in order to avoid and reduce the cost of a functional failure. This function could be further divided into subfunctions which is measuring mechanical wear with sensors, converting the signals to data and analyzing the data. Since this thesis is restricted to only process the mechanical part of a condition monitoring system the two last mentioned functions will be skipped. The function measuring mechanical wear with sensors remains. The function could be further divided into which subfunctions which defines what parameter the sensor should measure. Once the parameters are concluded they could once again be divided into the following:

- Which range should the sensor measure?
- Which accuracy should the sensor have?
- Which response time should the sensor have? Also known as P-F interval.

The result is summarized in table 5 and an overview of the functions is illustrated in figure 33.

Table 5, overview of parameters and their desired functions.

Parameter	Sensor range	Sensor accuracy	Sensor response time
Solid particles in oil	Particles > 4µm - 0-20.000 p/ml Particles > 6µm - 0-5000 p/ml Particles > 14µm – 0-640 p/ml	±5%	1 time / hour
Humidity in oil	0-20.000 PPM	±5%	1 time / hour
Rotation speed	0-2.000 RPM (up to 5.000rpm)	±1%	1 time / 10 ms
Torque	0-100.000Nm / 0-300.000Nm*	±1%	1 time / second
Vibration	0-50 mm/sec	±5%	1 time / 10 ms
Flow	0-20 l/min	±5%	1 time / second

*For larger applications.

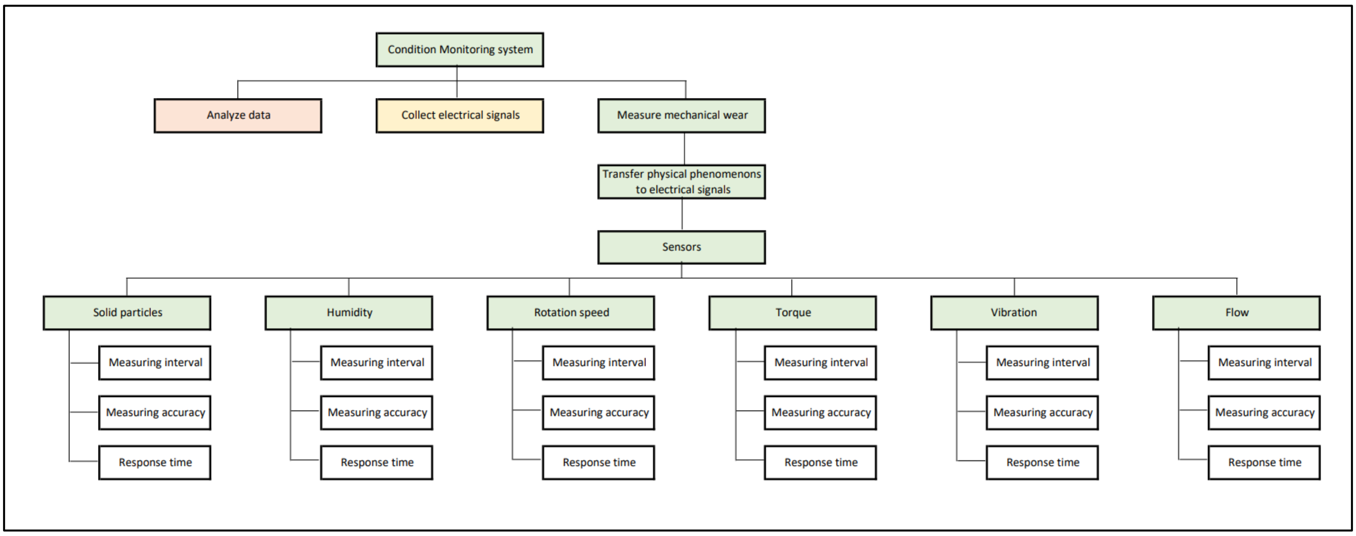

Figure 33, overview of the function tree.

3.3 Concept generation

The thesis work involves finding the most valuable Condition Monitoring system which complies with regulations from the classification societies. Therefore, it was never an objective to investigate new measurement methods but rather finding existing measurement methods and sensors. One of the used methods to find concepts was the catalogue method.

The concepts are to be based on the requirements specification. The objective in the concept generation is that every concept should comply and fulfill the requirement specification. As the CM-system consists of several measurement methods the concept was also divided into the following sub concepts:

- Concept for a control cabinet.
- Concept for measuring solid particles in hydraulic oil.
- Concept for measuring humidity in hydraulic oil.
- Concept for measuring rotation speed of the shaft.
- Concept for measuring torque of the shaft.
- Concept for measuring vibrations.
- Concept for measuring hydraulic flow.

This approach enables a process where the best sub concepts could be picked to receive the most valuable and reliable Condition Monitoring system.

3.4 Concept selection

The concept selection was divided into three steps as described by Ulrich and Eppinger. The Pahl and Beitz matrix eliminated all concepts that was not able to withstand the requirements from the classification society and Kongsberg Maritime. Further on, the Pugh's relative decision matrix was used to evaluate and rank the desired criterions of the concepts which passed the elimination matrix. The concepts were evaluated with the same weight on each criterion. As a last step a weighted Kesselring matrix was used which also evaluate and rank the concepts based on their weight and importance. The weight was set from 1 which is lowest importance to 5 which is considered a high importance. The weights of each criterion were set based on input from the project owner, Kongsberg Maritime. The usage of two different evaluation tools enables a higher confidence in the concepts. The result of the concept selection process is presented in corresponding heading below. All concept selection matrixes could be found in appendix B.

3.4.1 Control cabinet selection

All of the concepts passed through the elimination matrix. The elimination matrix consisted of requirements from the classification societies and a requirement of size to fit the control module from Kongsberg. The desires of the cabinet were a combination of price, robustness, simplicity and the fact that the cabinet followed Kongsberg color palette. A cabinet concept selection overview could be seen in table 6.

The chosen cabinet has a DNV-GL certificate which means that it is approved by the DNV classification society to be used in marine application. The cabinet has the same color code as Kongsberg standard code which is RAL 7035. Furthermore the cabinet has a hinged and removable door with a three-point locking mechanism that could be unlocked with a special key. The cabinet has a IP66 classification which ensures that the cabinet is protected from total dust ingress and protected from high pressure water jets from any direction. The cabinet also has a IK10 classification which proves that the cabinet could resist an impact energy of 20 joules according to the standard. The dimension of the selected cabinet is 250x200x150mm and the requirement to fit the control module is approximate 130x60x80mm, where the length could be extended, depending on how many modules that is needed. The selected size also enables an easier assembly of the control module and electrical cables inside the cabinet. Selected cabinet has a slightly higher price than the compared cabinets but since the selected cabinet has the correct color code and a DNV GL certificate it will become cheaper than the other concepts in the long run.

Table 6, overview of the evaluation process for the cabinet.

Cabinet	Elimination	Relative matrix [Rank]	Kesselring matrix [Rank]	Selected Concept
Concept 1	Passed	5	2	
Concept 2	Passed	3	2	
Concept 3	Passed	4	3	
Concept 4	Passed	1	1	X
Concept 5	Passed	2	4	

3.4.2 Solid particle measurement selection

As could be seen in table 7, four concepts failed the elimination matrix due to environmental requirements. The first requirement is that the components are to be able to withstand a temperature range of ±0°C to 55°C where concept 1 and concept 2 failed. The second requirement is that the equipment is to be able to withstand a hundred percent humidity in all temperatures where concept 7 and concept 8 failed. The elimination matrix consisted of requirements from the classification societies and requirements from Kongsberg Maritime. The relative matrix and the Kesselring matrix consisted of the desires from Kongsberg Maritime in combination with desires from the functional specification. The general desires for all sensors are a low price, small size, secure and reliable supplier and that the sensor could measure more parameters. Specific desires for solid particle measurement are that the accuracy should be less than ±5%, that measurement values was not presented on the sensor, sample frequency should be at least once in one hour and that the sensor could determine the particles chemical composition.

After reviewing the concepts with relative and Kesselring matrixes, Concept 6 was selected. Concept 6 is less expensive than concept 5. The selected concept is also produced by the same company as other selected sensors. The measurement is illustrated in a sequence signal with ISO values where the accuracy is ± 1 ISO-code. The sensor does not have a LED screen which is presenting live values which was a desire from Kongsberg.

Table 7, overview of the evaluation process for the particle counters.

Solid Particles	Elimination	Relative matrix [Rank]	Kesselring matrix [Rank]	Selected Concept
Concept 1	Failed	-	-	
Concept 2	Failed	-	-	
Concept 3	Passed	3	4	
Concept 4	Passed	2	3	
Concept 5	Passed	2	1	
Concept 6	Passed	1	2	X
Concept 7	Failed	-	-	
Concept 8	Failed	-	-	

The selected particle counter uses the laser light extension procedure which means that a laser and a photo diode measures the sizes of the particles. One highly weighted desire from Kongsberg was that the sensor could also measure the chemical composition of the particles, but none of the measuring methods which translates particle size to ISO code could decide the chemical composition. Therefore a second measurement method were added which further on will be called the material decision sensor. The concepts for the material decision sensor also went through the elimination matrix, a relative matrix and a Kesselring matrix. The second concept failed the elimination matrix due to its humidity range. The evaluation process is illustrated in table 8.

The selected concept is a ferromagnetic sensor which uses a magnet to attract ferrous material. It had a better price, is smaller and has a simpler measuring method than concept 3. Its measuring accuracy is ± 5% which is desired.

Table 8, overview of the evaluation process for the material decision sensor.

Material decision	Elimination	Relative matrix [Rank]	Kesselring matrix [Rank]	Selected Concept
Concept 1	Passed	1	1	X
Concept 2	Failed	-	-	
Concept 3	Passed	2	2	

3.4.3 Humidity measurement selection

The procedure for evaluation of humidity measurement is the same as previous concepts. All of the concepts pass the elimination matrix and the selection is therefore based on how well the concept fulfills the desires. The general desires for all sensors have been described in ***Subsection 3.4.2.*** The specific desires for humidity measurements were that the measuring accuracy should be less than ±5%, that the sample frequency should be at least once in one hour, that the sensor is able to recalibrate itself and that the sensor is able to detect and measure salt and iron levels. Concept 3 is based on a humidity sensor which is built into a particle counter which was not selected due to a much higher price. The evaluation of concept 3 was therefore based on the fact that this particle counter was selected. Concept 3 was therefore scrapped. The other concepts are separated sensors where concept 4 and 5 scores equally which is illustrated in table 9.

Concept 4 and Concept 5 received the same scoring point in both evaluation matrixes. Concept 4 is a little bit more expensive but it could also be used as an oil condition sensor which means that it could determine if the oil has been changed or if it needs to be changed. This fact does not only give the system owner more data to review at a potential failure analyze, but it could also be used to avoid changing oil that is in good condition. The extra measurement is a good solution both with the environment and the shipowner in mind.

Table 9, overview of the evaluation process for the humidity sensor

Humidity	Elimination	Relative matrix [Rank]	Kesselring matrix [Rank]	Selected Concept
Concept 1	Passed	3	5	
Concept 2	Passed	4	4	
Concept 3	Passed	1	1	
Concept 4	Passed	1	2	X
Concept 5	Passed	1	2	
Concept 6	Passed	2	3	

3.4.4 Rotation speed measurement selection

Due to the fact that many users of torque sensors are both interested in torque and power, most of the so-called torque measurement methods also have a built-in rotational speed sensor. Power could be calculated by multiplying the Torque with the angular speed [rad/sec] which could easily be manipulated to rotational speed [Revolutions/min]. Due to the fact that all Torque measurement concepts has a built-in rotation speed sensor, no concepts on rotational speed were created.

3.4.5 Torque measurement selection

Five different concepts for torque measurement were found in the concept generation process. The first concept failed the elimination matrix as it could introduce a new weakest point of the shaft assembly and due to the environmental working conditions could not be confirmed. The general desires remain the same as already mentioned. The specific desires for the torque sensor are that the measurement accuracy should be ±1%, that the sample frequency should be at least once a second and that the assembly should be robust and safe. The result of the evaluation process is illustrated in table 10.

Concept 2 was selected on the fact that it scored highest on both evaluation matrixes. The selected concept is a strain gauge-based sensor built for marine applications. It has an output signal of 4-20mA and could be mounted around an existing shaft which means that the shaft assembly is neither changed or that any new weak point is introduced. It also has a built-in rotational speed sensor which pulse signal is translated to a 4-20mA current signal in a control unit.

Table 10, overview of the evaluation process for the torque sensor

Torque	Elimination	Relative matrix [Rank]	Kesselring matrix [Rank]	Selected Concept
Concept 1	Failed	-	-	
Concept 2	Passed	1	1	X
Concept 3	Passed	4	3	
Concept 4	Passed	3	4	
Concept 5	Passed	2	2	

3.4.6 Vibration measurement selection

Six different concepts for measuring vibration were found. Concept 6 failed the elimination matrix as it did not have any IP value specified. The general desires were once again used together with the specific desires. The specific desires were that the accuracy should be ±5%, sample frequency 10 ms and that the sensor could measure acceleration in 3 axis. The result of the evaluation process is illustrated in table 11.

Concept 2 scored the highest points in the evaluation process. But the sensor could only be mounted vertically and therefore vibration could only be measured vertically and not horizontal. Concept 4 has one sensor within the same family which could measure vertically and one sensor which could measure horizontal. Choosing one sensor manufacturer for vertical measurements and one other for horizontal measurements does not make any sense. The selected sensor also has several connection options which makes it more adjustable.

Table 11, overview of the evaluation process for the vibration sensors.

Vibration	Elimination	Relative matrix [Rank]	Kesselring matrix [Rank]	Selected Concept
Concept 1	Passed	3	3	
Concept 2	Passed	1	1	
Concept 3	Passed	3	4	
Concept 4	Passed	2	1	X
Concept 5	Passed	2	2	
Concept 6	Failed	-	-	

3.4.7 Flow measurement selection

The flow measurement concepts are the last concepts which were evaluated. Concept 4 and concept 9 failed the elimination matrix. Concept 4 failed on its ability to withstand humidity and concept 9 because its measuring interval was too low. The general desires remain the same as previous concept and the specific desires are that the accuracy should be ±5%, that the sample frequenze should be once a second and that the measuring interval should be 0 to 20 liters per minute. The evaluation process is illustrated in table 12.

Concept 7 is a mechanical flow sensor which received the highest score in both the relative and Kesselring matrix. It has a G ½ connection which enables it to be mounted directly on the pressure line. It has a relatively low price even though the product comes from a well-known producer. The product will require some small changes in the hydraulic system because some pressure drop will be introduced. It has a measuring interval of 0,5l/min to 25l/min.

Table 12, overview of the evaluation process for the flow sensor.

Flow	Elimination	Relative matrix [Rank]	Kesselring matrix [Rank]	Selected Concept
Concept 1	Passed	3	4	
Concept 2	Passed	2	3	
Concept 3	Passed	2	4	
Concept 4	Failed	-	-	
Concept 5	Passed	4	5	
Concept 6	Passed	4	5	
Concept 7	Passed	1	1	X
Concept 8	Passed	2	2	
Concept 9	Failed	-	-	

3.4.8 Summarize of the selection

The concept selection process has eliminated concepts which has not fulfilled the requirements from either the classification societies or Kongsberg Maritime with the elimination matrix. The process has evaluated the desires based on two matrixes to ensure that the correct decision has been made. The concepts are now part of a system and will from this moment not be called concepts anymore. The selected concepts and their new name have been summarized in table 13.

Table 13, overview of selected concepts and the corresponding name.

Measured parameter	Selected concept	Corresponding name
Cabinet	Concept 4	Protection cabinet
Particle concentration	Concept 6	Particle counter
Chemical composition	Concept 1	Ferromagnetic sensor
Humidity	Concept 4	Humidity sensor
Torque	Concept 8	Torque & RPM sensor
Vibration	Concept 4	Vibration sensors
Flow	Concept 7	Flow sensor

4 Result

4.1 Cabinet function and configuration

The cabinet has a hinged and lockable door. It has a bottom plate where an electrical quick coupling will be fitted to ease installation, see figure 34. The cabinet is painted in RAL 7035 which is Kongsberg standard color. The size of the cabinet is somewhat larger than the control module which decreases the risk of overheating the module. The cabinet is also produced in series which means that the same cabinet could be ordered which have larger sizes, if for example more control modules are added, which could not fit in this specific cabinet. The cabinet has an external DIN-rail installed inside which the control module easily could be mounted at. The cabinet also has a certificate from DNV-GL which ensures that the cabinet could be used within marine environments. The size of the cabinet is 250mm height, 200mm width and 150mm deep.

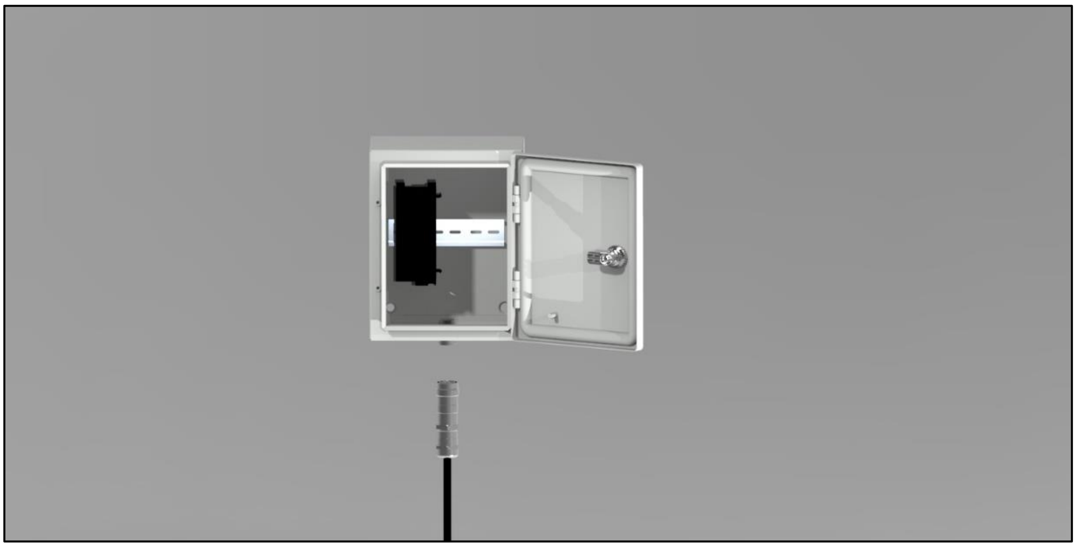

Figure 34, 3D visualisation of the control module mounted on a DIN rail inside the selected cabinet.

4.2 Sensor function and configuration

4.2.1 Particle counter

The particle counter uses the light extension principle, it is a so-called light scattering particle counter. It consists of a measuring cell (a), a laser beam (b) and a photo diode (c). Once a particle passes the laser beam the intensity of light detected by the photo diode is reduced. The larger particle the more reduction in intensity. The function is illustrated by figure 35.

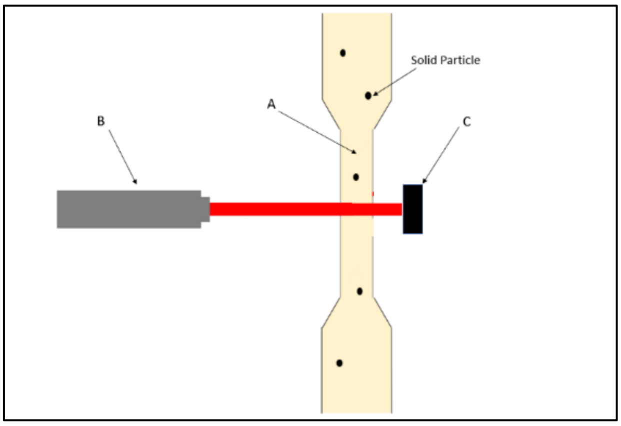

Figure 35, illustration of the function of a particle counter.

During the measurement process the particle counter divides the counted particles into different size groups according to ISO standard ISO 4406:1999. Once the measurement process is completed the particle counter sends out a so-called sequential signal. Each sequence starts with a 20mA current pulse in four seconds which could be used as a starting signal in the control module. The start pulse is thereafter followed up by another four pulses between 4-20mA which are active for 2 seconds each. The first pulse represents particles per millilitre which is larger than 4µm, the second pulse represents particles larger than 6µm, the third pulse represents particles larger than 14µm and the last pulse represents particles larger than 21µm. The sequential signal is illustrated in figure 36.

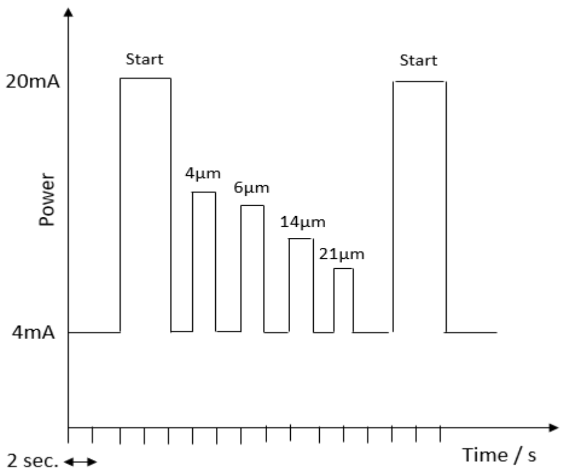

Figure 36, sequential signal output.

The four pulses represent four different intervals of particle sizes and the current output represents the amount of particles per millilitre in that specific interval. The higher current value (mA) the more amount of particles is present in the oil. The amount of particles per millilitre could be translated to a specific ISO-code. In order to make the ISO-code proportional to the output current a linear equation needs to be established. It is of interest to find the ISO-code based on the current value (mA). Equation 4 shows a typical linear equation in K-form. K is the slope of the curve, m is a constant and x is the known value, in this case the current. The slope could be calculated by using equation 5. It is known that the ISO-code goes from 0 to 26 which gives that the numerator is 26. It is also known that the current goes from 4 mA to 20mA which gives that the denominator is 16. By dividing the values, it is given that the slope is 1,625. Since it is also known that ISO-code 0 is 4mA, it is possible to find the constant m, which is found to be 6,5. Summarizing this gives equation 6, which could be reorganized to establish equation 7. Equation 7 enables the possibility to summarize each ISO-code to a specific current value, which is shown in table 14.

Equation 4: $$y = kx + m$$

Equation 5: $$k = \frac{y_2 - y_1}{x_2 - x_1}$$

Equation 6: $$ISO - code = (1{,}625 \times Current\ [mA]) - 6{,}5$$

Equation 7: $$mA = \frac{ISO - code + 6{,}5}{1{,}625}$$

Table 14, summarize of the corresponded current to each ISO-code.

ISO-code	Current value [mA]	More than [p/ml]	Up to and including [p/ml]
0	4	0	1
1	4,62	1	2
2	5,23	2	4
3	5,85	4	8
4	6,46	8	16
5	7,08	16	32
6	7,69	32	64
7	8,31	64	130
8	8,92	130	250
9	9,54	250	500
10	10,15	500	1.000
11	10,77	1.000	2.000
12	11,38	2.000	4.000
13	12,00	4.000	8.000
14	12,62	8.000	16.000
15	13,23	16.000	32.000
16	13,85	32.000	64.000
17	14,46	64.000	130.000
18	15,08	130.000	250.000
19	15,69	250.000	500.000
20	16,31	500.000	1.000.000
21	16,92	1.000.000	2.000.000
22	17,54	2.000.000	4.000.000
23	18,15	4.000.000	8.000.000
24	18,77	8.000.000	16.000.000
25	19,38	16.000.000	32.000.000
26	20,00	32.000.000	64.000.000

This specific particle counter could measure from ISO-code 0 to 24 but it has a calibrated range between ISO-code 10 to 22 which is illustrated with a green background in table 14. Kongsberg Maritime defines two different ISO cleanliness codes of interest. The first ISO-code will be used to send a so-called low alert which recommends the customer to act, it will be set when the oil cleanliness reaches 19/16/13. The second ISO-code will be a high alert which prompts the user to act immediately and will be set when the oil cleanliness reaches 21/19/16. It is now known which ISO-codes that are of interest and by using table 14, the ISO-codes could be translated to a current which could be used as a threshold. The ISO-codes of interest and their corresponding current is summarized in table 15.

Table 15, summarize of the thresholds.

	Low alert			High alert		
ISO-code	19	16	13	21	19	16
Current threshold [mA]	15,69	13,85	12,0	16,92	15,69	13,85
Required action	Check hydraulic oil and hydraulic system			Contact Kongsberg Maritime		

4.2.2 Ferromagnetic sensor

The sensor uses a magnet to attract ferromagnetic particles to the sensor lens. Once the lens is filled with particles the magnet releases the particles into the system again. The more particles present in the system the quicker the lens will be filled. The fact that the sensor only attracts ferromagnetic particles enables the possibility to evaluate if the system contamination is ferrous on non-ferrous materials. The interest of the measurement lies in the amount of time it takes to fill the lens rather than the fact that the lens is filled. Measuring the parameter without time perspective does not provide any useful information. The function of the sensor is explained in figure 37.

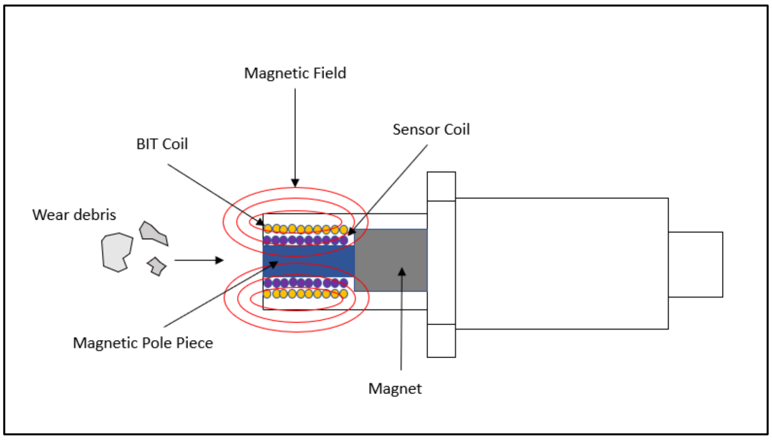

Figure 37, function description of the ferromagnetic sensor.

The sensor output is a 4-20mA current which is proportional to how much of the sensor lens that is filled with particles in an interval between 0% to 100%. The quicker the sensor lens is filled, the more ferrous particles are present in the system. The left-hand graph in figure 38 illustrates signal data where the lens is slowly filled while the right-hand graph in figure 38 shows signal data where the lens is more quickly filled. Looking at the examples in figure 38 it becomes clear that the slope of the curves could potentially be used as a condition monitoring task, but as per now, the expected values of the slope are unknown which disables this opportunity. However, it could be worth investigating further after this thesis to receive a more understandable and well-defined parameter which could be defined as filling percent per second and equation 8 shows an example.

Equation 8: $$Filling\ percent\ per\ second\ [\%/sek] = \frac{100}{Curve\ end\ time\ [s] - Curve\ start\ time\ [s]}$$

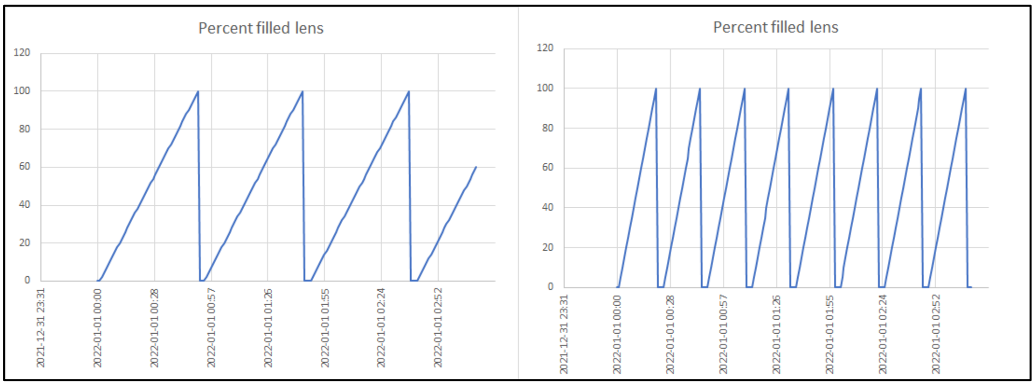

Figure 38, the left-hand graph shows a slowly filled lens while the right-hand side shows a quickly filled lens.

Using the same method as described for the particle counter, a linear equation could be established, equation 9. Reorganizing equation 9, gives equation 10 which could be used to find the corresponding current for each percent. The equation could be used to find the rough values illustrated in the graph in figure 39. As described earlier in this section the signal must be classified as a surveillance task until further testing has been performed, which is why no thresholds are calculated.

$$\textit{Equation 9:} \quad Percent\ [\%] = (6{,}25 \times Current\ [mA]) - 25$$

$$\textit{Equation 10:} \quad mA = \frac{Percent\ [\%] + 25}{6{,}25}$$

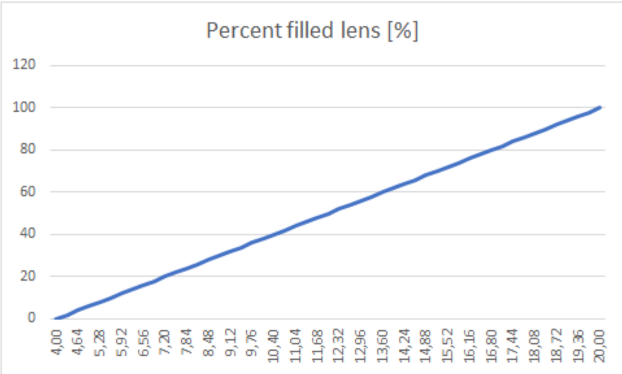

Figure 39, graph of the ferromagnetic signal values.

4.2.3 Humidity sensor

Typically, a humidity sensor only measures the relative humidity and the temperature but the selected sensor enables more parameters to be measured. Except the temperature and the amount of water in the oil the sensor could also communicate the conductivity and the permittivity of the oil. The parameters could be used to understand the condition of the hydraulic oil. The sensor output is a sequential 4-20mA output. The sequential starts with a four second starting signal followed by eight two second pulses where the current is proportional to the parameter it measures. The sequential output is illustrated in figure 40 and the shorting's are explained in table 16.

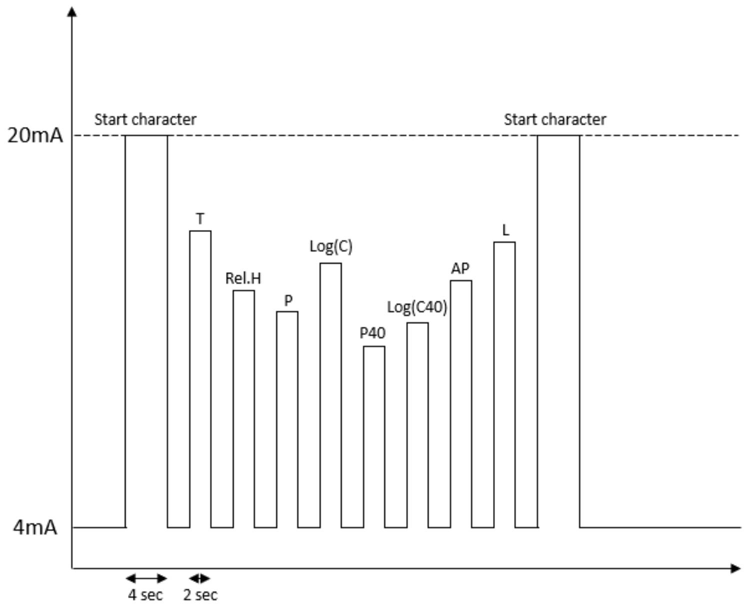

Figure 40, the sequential output signal of the humidity and oil condition sensor.

Table 16, overview of the shorting for figure 38.

Shorting	Description
T	Temperature
Rel. H	Relative humidity [%]
P	Permittivity
C	Conductivity
P40	Relative permittivity at 40 °C
C40	Conductivity at 40 °C
AP	Aging process
L	Filling level (Not applicable)

Humidity

The selected sensor is a capacitive humidity sensor which measures the parameter relative humidity (φ). Relative humidity is a parameter which is known as the percentual ratio between the actual water contained in the oil and the maximum possible amount of dissolved water at the saturation limit. While absolute humidity is variable depending on both oil producer and temperature, the relative humidity parameter remains reliable no matter what kind of oil it measures or which temperature it measures in. The sensor provides a current pulse which is included in the sequence signal described earlier. The pulse current is proportional to the measuring interval which in this case is 0% to 100%. Since both the current and the parameter intervals are known it could be placed in a linear equation as shown in equation 11. Equation 11 could be reorganized and forms equation 12 which could be used to illustrate the curve of figure 41.

$$\textit{Equation 11:}\quad Relative\ humidity\ [\%] = (6{,}25 \times Current\ [mA]) - 25$$

$$\textit{Equation 12:}\quad mA = \frac{Percent\ [\%] + 25}{6{,}25}$$

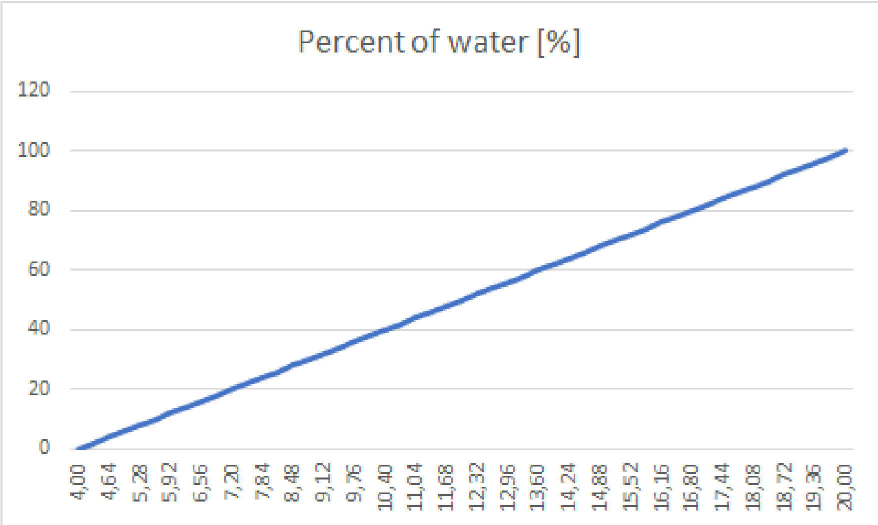

Figure 41, graph of the relative humidity vs. mA current.

Going back to the theory, it was found that the output interval could be further divided into three intervals with three different working conditions which enables to set thresholds for alarm. The threshold for low alarm could therefore be set at 40% and the threshold for high alert could be set at 60%, according to table 4. Using equation 11 the thresholds could now be interpreted to a corresponding current threshold, which is summarized in table 17. The result is that a low alert is set if the sensor current exceeds 10,4mA and a high alert is to be set if the sensor current exceeds 13,6mA.

Table 17, overview thresholds for humidity in oil and potential alerts.

	Low alert	High alert
Relative humidity [%]	40	60
Current threshold [mA]	10,4	13,6
Required action	Check oil and hydraulic installations	Contact Kongsberg Maritime

The fact that oil could absorb less water in low temperatures could potentially lead to severe number of misleading alerts for the end user. Therefore it might be a good idea to integrate the temperature to the alert aswell. This could be done by using a so-called “AND-function” within programming. This means that in order to set an alert on relative humidity also the temperature of the oil needs to be above a certain temperature.
For example, in order to set a high or low alert regarding humidity also the signal from the temperature sensor must exceed a certain current. The amount of water in the oil during start-up could be an interesting parameter, but it could also lead to huge number of misleading alerts since the oil yet not have been circulated and that the oil hasn’t reach its working temperature yet.

Temperature

The temperature of the hydraulic oil is used to calculate the relative humidity which also enables the possibility to include it in the condition monitoring system. The signal is represented as the first pulse of the sequential signal. It is proportional to its measuring interval which is -20°C to +85°C. The linear equation for the temperature could be found at equation 13. Equation 13 could as always be reorganized to equation 14 if the mA is unknown. Equation 14 could be used to find the current which is corresponding to each temperature, a summarize is visualized figure 42.

$$\text{Equation 13:} \quad Temperature\,[°C] = (6{,}5625 \times Current\,[mA]) - 46{,}25$$

$$\text{Equation 14:} \quad mA = \frac{Temperature\,[°C] + 46{,}25}{6{,}5625}$$

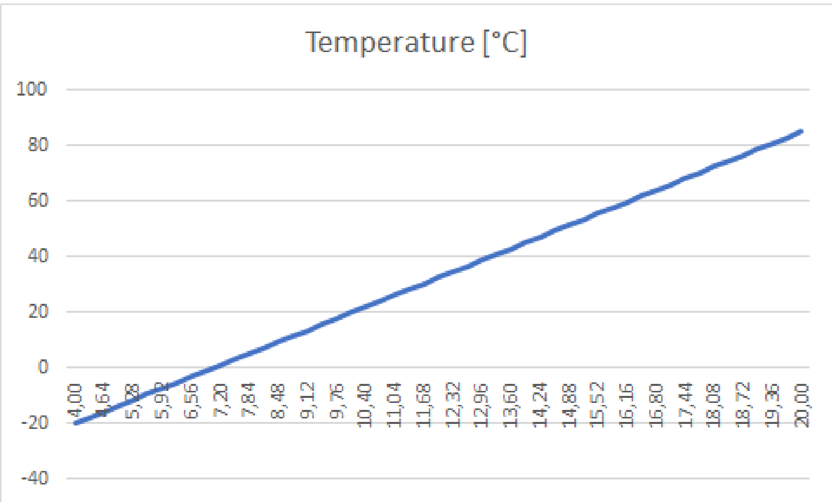

Figure 42, illustration of temperature vs. mA current.

Conductivity and permittivity

The selected humidity sensor could also measure conductivity and permittivity which were not an objective in this thesis and will therefore only be mentioned shortly. Both the conductivity and the permittivity could be used to determine if the hydraulic oil needs to be replaced, if it has been mixed with other oils or if the oil has been replaced. It could be a good feature to have if Kongsberg Maritime for example wants to provide an annual report for the ships which are enrolled for condition monitoring. Such report could lead to reduced waste of good oil which in the long run is good for the environment. Linear equations for the parameters are established in equation 15 and 16. The parameters are the third and the fourth pulses on the sequential signal.

$$\textit{Equation 15:} \quad Conductivity\ [\mathrm{pS/m}] = (49993{,}75 \times Current\ [mA]) - 199975$$

$$\textit{Equation 16:} \quad Permittivity = (0{,}4375 \times Current\ [mA]) - 1{,}75$$

Conductivity

Electric conductivity is a measurement of how well the liquids electrostatic chargeability is. The conductivity is variates with different oils and with different batches, which means that oil changes, oil mixtures and contaminations could be seen as, either a decrease or increase in the conductivity. The conductivity could also be increased if salt, acids or bases are found in the oil. Due to mentioned perks and features it could be a good idea to have the data available in a failure analysis. If the shipowner for example fills the hydraulic system with oil that has already been contaminated with water, the sensor could see that the conductivity changes at the same time as the humidity level increases.

Permittivity

Relative permittivity of an oil is an indicator for its polarity. Oils often changes their polarity during an aging process which is why this parameter could be used to identify if the oil needs to be replaced. However, both of those parameters are highly temperature dependent which is why it has own pulses in the sequential signal that is converged to a temperature of 40°C. Checking the parameters over time should therefore be done with pulse five and six. As mentioned earlier, those parameter has not been an objective of this thesis and therefore it hasn’t been further investigated.

4.2.4 Torque & RPM sensor

The selected system uses the strain gauge method to determine applied torque on the shaft. The signal from the strain gauge sensor is transferred to a Wi-Fi transmitter which forwards the signal to a control unit. The Wi-Fi transmitter and the strain gauge sensor is powered by an inductive rotor and stator which enables electrical power to be transmitted without any mechanical connection. Inside the rotor there is also a magnet which presence is accumulated by the stator to determine the rotational speed. The system is further visualized in figure 43.

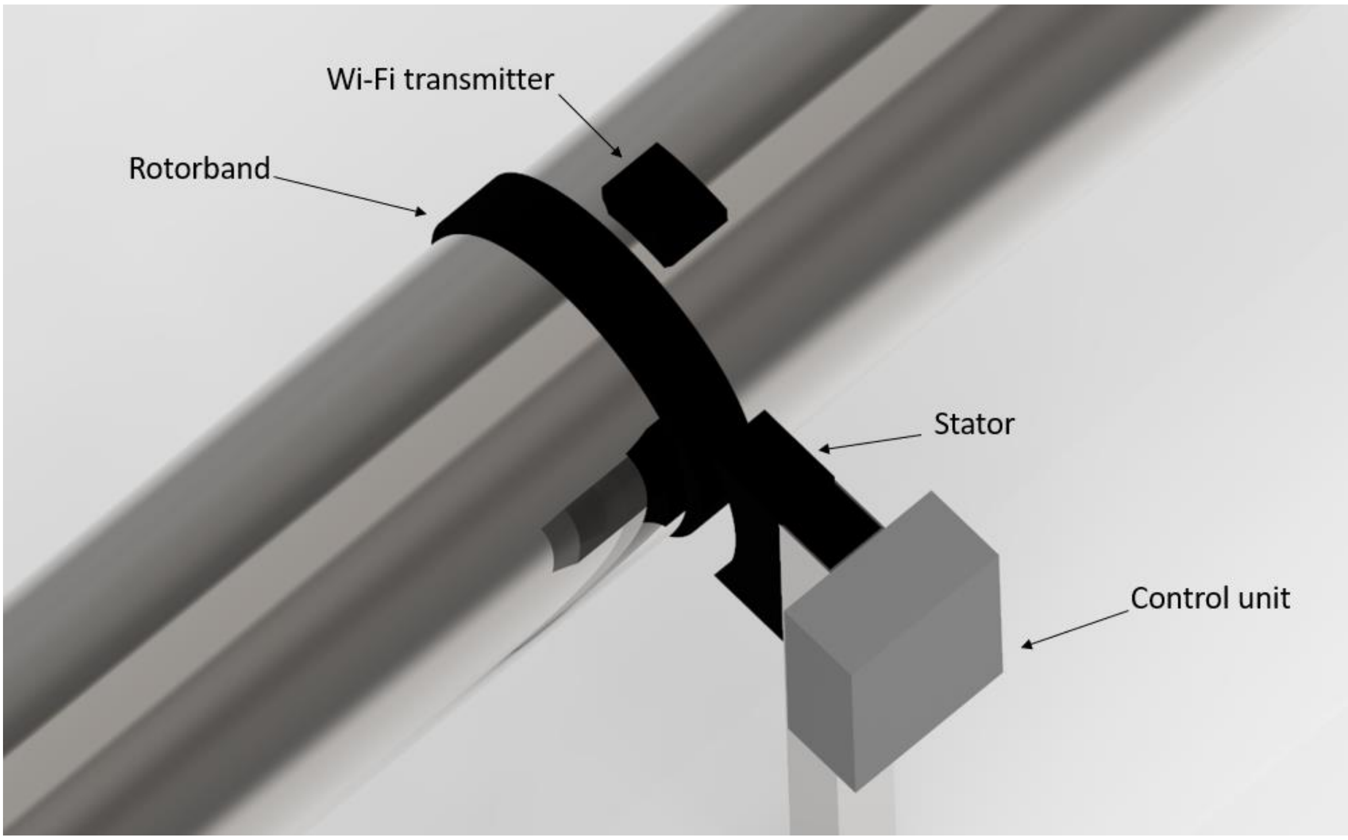

Figure 43, simplified example of the function for the torque sensor assembly.

The relationship between the applied torque and the output current could be found using the same method as previous, but since the torque interval is different for different applications as a first step the interval needs to be divided. The first interval is for products which has an applied torque below 100kNm, the second interval is for products which has an applied torque below 200kNm and the last interval is for products which has an applied interval below 300kNm. This will also give three different linear equations. Equation 17 represents the first interval, equation 18 represents the second interval and equation 19 represents the last interval. Equation 17, 18 and 19, gives equation 20, 21 and 22 which could be used to establish the graph shown in figure 44.

Equation 17: $$Applied\ Torque\ [kNm] = (6{,}25 \times Current\ [mA]) - 25 \leftarrow Products\ below\ 100kNm.$$

Equation 18: $$Applied\ Torque\ [kNm] = (12{,}5 \times Current\ [mA]) - 50 \leftarrow Products\ below\ 200kNm.$$

Equation 19: $$Applied\ Torque\ [kNm] = (18{,}75 \times Current\ [mA]) - 75 \leftarrow Products\ below\ 300kNm.$$

Equation 20: $$mA = \frac{Applied\ Torque\ [kNm] + 25}{6{,}25}$$

Equation 21: $mA = \frac{Applied\ Torque\ [kNm] + 50}{12{,}5}$

Equation 22: $mA = \frac{Applied\ Torque\ [kNm] + 75}{18{,}75}$

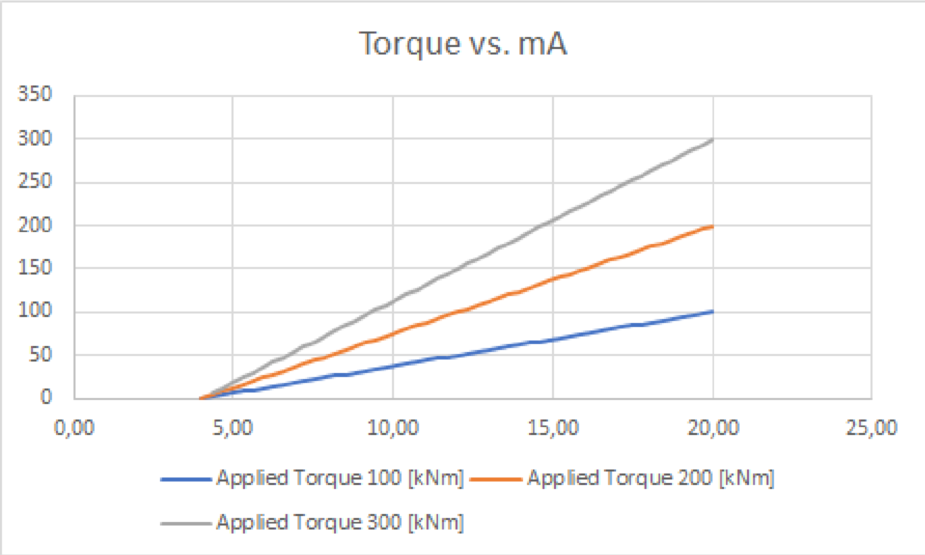

Figure 44 graph of applied torque vs. mA.

This means that if no torque is applied the readings of the output current will be 4mA for all intervals. If the applied torque would be 10kNm the readings of the first interval would be 5,6mA, the readings of the second interval would be 4,8mA and the readings of the last interval would be 4,53mA. The interval needs to be chosen carefully due to the fact that a large interval could affect the accuracy of the system. Intervals could also be set for each and every application to receive the most efficient and accurate system. This could be done by creating a linear equation specific for that interval, equation 23.

Equation 23: $Applied\ torque\ [kNm] = (\frac{Maximum\ torque\ [kNm]}{16}) \times Current[mA] - ((\frac{Maximum\ torque\ [kNm]}{16}) * 4)$

Rotational speed

The sensor system also has a built-in rotational speed sensor. The sensor creates a pulse once the magnet inside the rotor passes the sensor. The time between each pulse could be used to determinate the rotational speed of the shaft. The control unit then converts the rotational speed to a 4-20mA signal which could be used in programming to determine the speed. To do so, once again a linear equation needs to be established, equation 24. It is known that the rotational speed of the shaft is maximum 2.000RPM. Reorganizing equation 24, gives equation 25 which could be used to create the curve shown in figure 45.

$$Equation\ 24:\quad Rotational\ speed\ [RPM] = (125 \times Current\ [mA]) - 500$$

$$Equation\ 25:\quad mA = \frac{Rotational\ speed\ [RPM] + 500}{125}$$

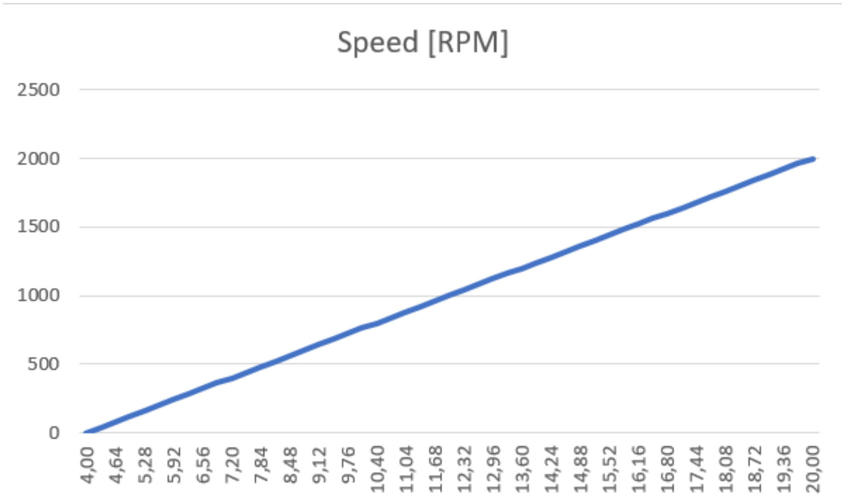

Figure 45, Rotational speed vs. mA current.

Power

The last parameter which will converted to a 4-20mA output signal is the power of the shaft. The power output on the shaft is a little more complicated since it has to do with both rotational speed and torque. Equation 26 shows the formula to calculate the power based on torque and angular speed while equation 27 shows a formula based on shaft speed in RPM.

$$\textit{Equation 26:}\quad Power\ [kW] = Torque\ [kNm] \times Angual\ speed\ [rad/s]$$

$$\textit{Equation 27:}\quad Power\ [kW] = Torque\ [kNm] \times Shaft\ speed\ [RPM] \times \frac{\pi}{30}$$

Shaft speed is known to be maximal 2000RPM while the torque once again could be divided into three intervals. The fact that torque is divided into three intervals also gives three power intervals which are illustrated in table 18.

Table 18, summarize of the maximum power for each torque interval.

	0-100 kNm interval	0-200 kNm interval	0-300 kNm interval
Power	≈ 21.000kW	≈ 42.000kW	≈ 63.000kW

Once the interval is known the linear equation for the power current output could be established. Equation 28, 29 and 30 are used based on the torque interval. If the power is known current could be found using equation 31,32 and 33. Figure 46 summarizes the three power intervals with three curves on a graph.

$$\textit{Equation 28:}\quad Applied\ Power\ [kW] = (1312{,}5 \times Current\ [mA]) - 5250 \leftarrow Products\ below\ 100kNm.$$

$$\textit{Equation 29:}\quad Applied\ Power\ [kW] = (2625 \times Current\ [mA]) - 10500 \leftarrow Products\ below\ 200kNm.$$

$$\textit{Equation 30:}\quad Applied\ Power\ [kW] = (3937{,}5 \times Current\ [mA]) - 15750 \leftarrow Products\ below\ 300kNm.$$

$$\textit{Equation 31:}\quad mA = \frac{Applied\ Power\ [kW] + 5250}{1312{,}5}$$

$$\textit{Equation 32:}\quad mA = \frac{Applied\ Power\ [kW] + 10500}{2625}$$

$$\textit{Equation 33:}\quad mA = \frac{Applied\ Power\ [kW] + 15750}{3937{,}5}$$

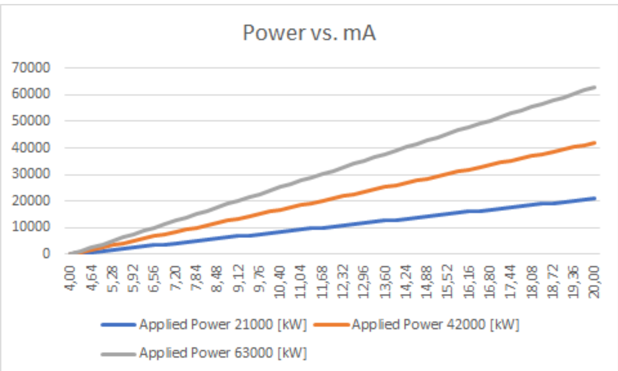

Figure 46, Applied power intervals vs. current mA.

4.2.5 Vibration sensor

The vibration sensor is to be used in order to measure vibrations at the bearing housing. Vibrations at the bearing housing could indicate a potential wear which could develop into a functional failure. The vibration sensor is a so-called velocity transmitter which means that the sensor automatically translates the vibration to a normalized signal. In this case a 4-20mA current which is proportional to the RMS velocity (mm/s). The sensor could measure velocities in an interval from 0mm per second to 100mm per second. A linear equation could therefore be established, see equation 34. Reorganizing equation 34, gives equation 35 which could be used to create the curve illustrated in figure 47. The allowed vibration level is highly affected by the placement and since there is no data available no thresholds could be set, but according to figure 30 and the ISO 10816 standard the velocity should not exceed 28mm/s for machines with a soft foundation.

Equation 34: $$Vibration\ [mm/s] = (6{,}25 \times Current\ [mA]) - 25$$

Equation 35: $$mA = \frac{Vibration\ [mm/s] + 25}{6{,}25}$$

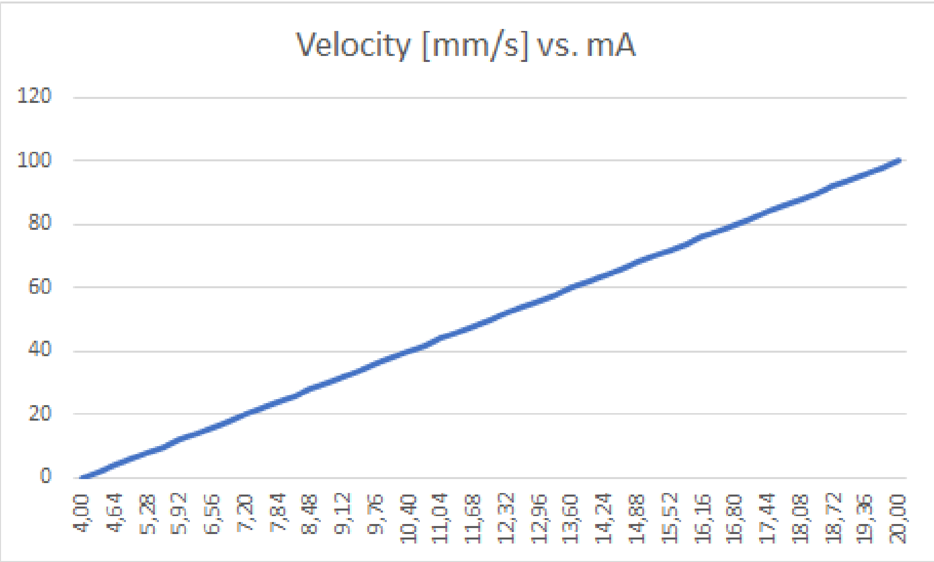

Figure 47, Velocity in mm/s vs. current mA

4.2.6 Flow sensor

The flow sensor consists of a spring-loaded piston and a potentiometer. The basic principle is that once flow is introduced, it will create a force which will act on the piston. The force from the fluid will compress the spring which will allow the piston to move and once the flow reduces the spring force will become larger than the force of the fluid which will force the piston to move back again. The movement of the piston could be measured with a potentiometer which enables the opportunity to manipulate the current based on the pistons location, hence, the flow rate. The measuring interval of the sensor is 0,5l/min to 25l/min. The linear equation for the flow sensor is established in equation 36. Reorganizing equation 36, gives equation 37 which could be used to find the current for specific flows which is illustrated with a curve in figure 48.

$$\textit{Equation 36:}\quad Flow\ [l/min] = (1{,}53125 \times Current\ [mA]) - 5{,}625$$

$$\textit{Equation 37:}\quad mA = \frac{Flow\ [l/min] + 5{,}625}{1{,}53125}$$

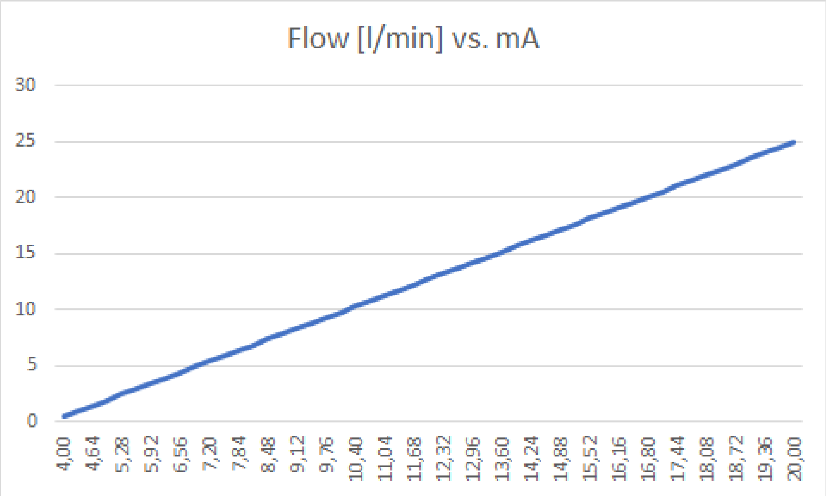

Figure 48, flow interval vs. current mA

The flow sensor will be installed on a lubrication system which provides hydraulic oil to bearings, this means that if the flow is reduced the bearing will not be enough lubricated and the oil temperature will increase. Kongsberg Maritime therefore has a desire of a lower flow threshold at 2l/min. If the flow goes below 2l/min an alert should be set. The lower threshold could be calculated by using equation 37 and is visualized in table 19. This means that if the current goes below 4,98mA and alert should be sent to the user to act.

Table 19, Threshold of the flow sensor.

	High alert
Flow [l/min]	2
Current [mA]	4,98

4.3 Cabinet design, placement and layout

One of the objectives in this thesis is to investigate the placement of the components and the sensors. The placement is decided by either regulations from the classification societies, by the parameter the sensor is going to measure or by the existing systems.

4.3.1 Control cabinet

Most of the waterjet systems are designed for ships where the engine room layout is already decided. This means that the cabinet must be somewhat portable. It needs to have an ability to be placed where the customer has a free spot for it. However, the cabinet has some rules and requirements from the classification society which has to be fulfilled. One of the rules is that the cabinet should be placed so that exposure of water, oil and steam is reduced as much as possible and that the cabinet is placed so that it is not likely to be stepped on. The cabinet is also a wall mounted cabinet which means that it should be mounted towards a wall in order to keep its protection degree. Also, in order to not reduce the protection degree, the electrical connector in the cabinets bottom needs to have a protection degree which is not lower than the cabinet degree. In order to ease installation the connectors need to be of quick type which allows pre-assembly of both control cabinet and the electrical harness. The cabinet will require a so-called DIN-rail where the control units could easily be installed. Figure 49 shows a section view of the cabinet where the structure of the DIN-rail could be seen.

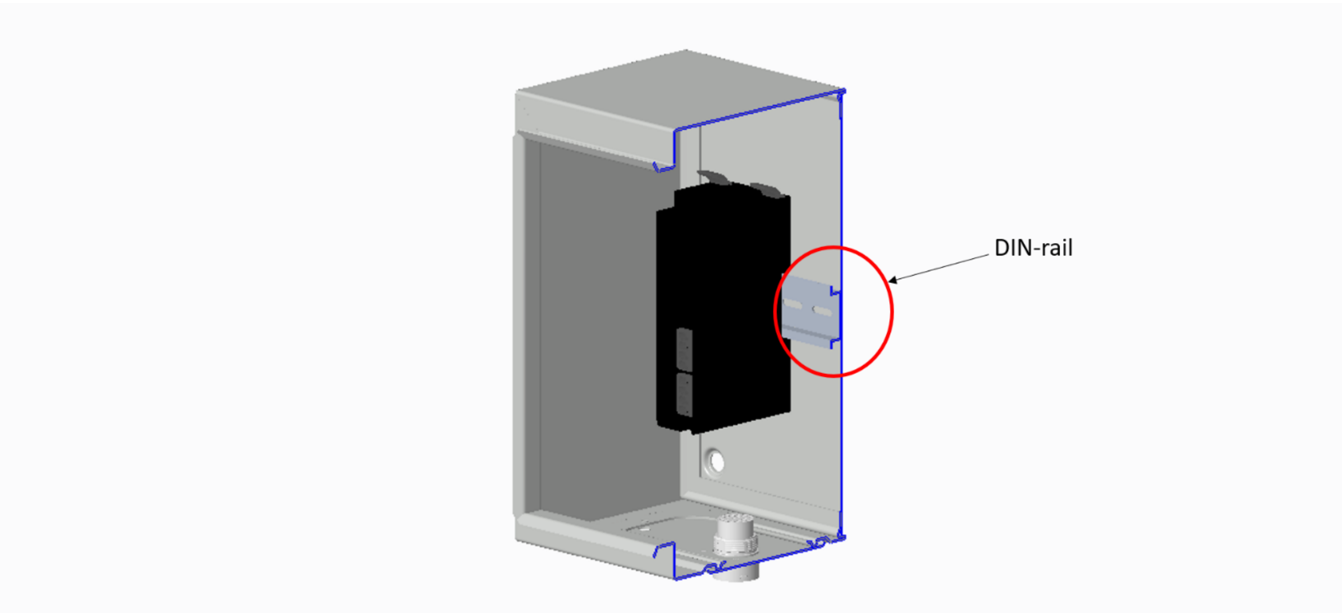

Figure 49, Section view of the cabinet with a so-called DIN rail.

4.4 Hydraulic sensors design, placement and layout

4.4.1 Existing hydraulic system layout

In order to understand the placement it is important to also understand the function and layout of the existing hydraulic system. The hydraulic system could be divided into one high-pressure system and one lubrication system. The high-pressure system is used to control the hydraulic cylinders which is designed to maneuvering the waterjet and the lubrication system is primarily used to lubricate bearings. The two systems share the same hydraulic tank which means that if one of the systems is contaminated by solid particles or water ingress, the other system will also become contaminated. This does not apply for the largest applications which has separated tanks and systems. The hydraulic pressure and flow for the lubrication system is produced by a separated lubrication pump. After the lubrication pump the oil is being cleaned in a filter before it enters a G ½" sized pressure line to the bearings. Once the oil has passed the bearings, it goes through a G 1" sized returning line to a pressure maintaining valve. The function of the pressure maintaining valve is to avoid pressure drop over the bearing. A simplified circuit of the system is shown in figure 50.

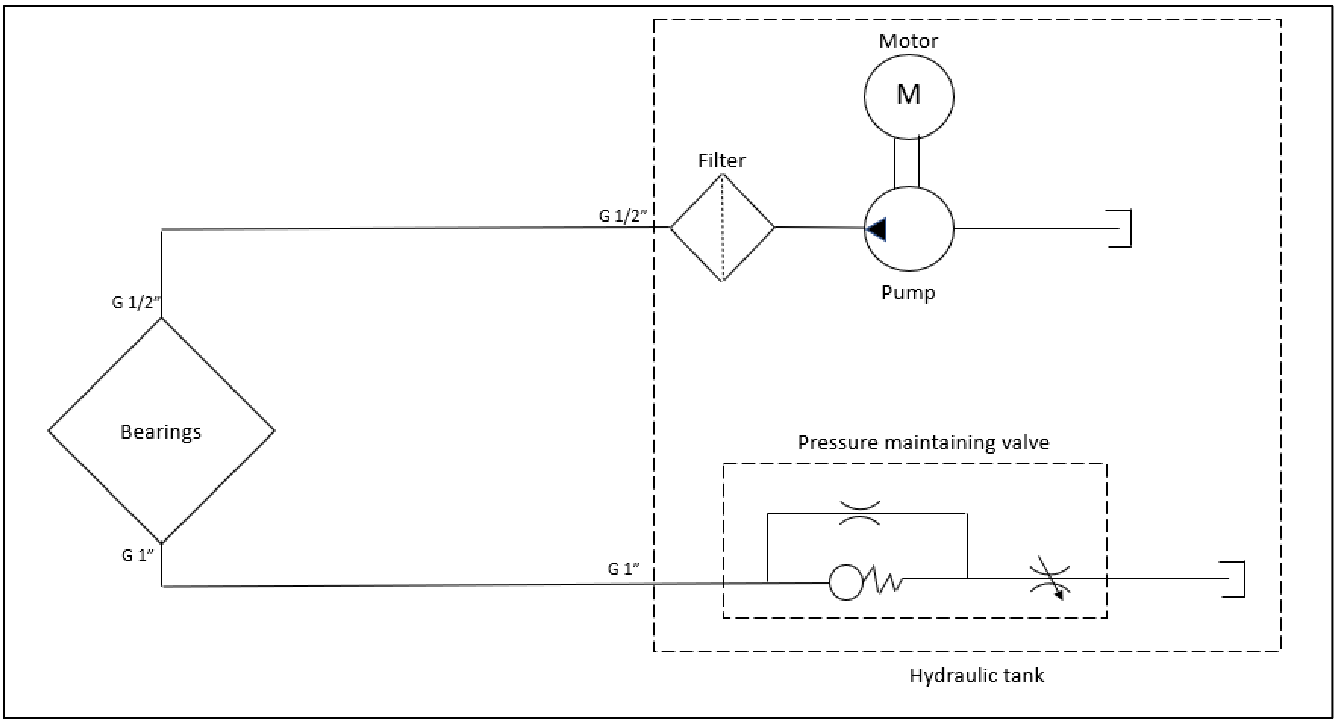

Figure 50, simplified overview of the existing hydraulic circuit.

4.4.2 Particle counter

The placement of the particle counter is pretty straight forward. The reason for measuring solid particles is to monitor the bearing, which means that a measurement before the bearing would not be suitable. The particle counter needs to be mounted after the bearing. The particle sensor has two main restrictions. The first restriction is that the particle counter is designed to measure in a flow between 50 to 400ml/min and the flow of the existing system lies within an interval between 6l/min to 17l/min. Due to the fact that the hydraulic pipe diameter is increased after the bearing from G½" to G1" the flow is somewhat reduced but not enough. The second restriction is the hydraulic connections sizes of the particle counter. The hydraulic connections of the selected particle counter are G¼" which means installing the particle counter directly on the returning line increases the flow even further. Those restrictions make it clear that some kind of parallel and flow-controlled circuit is needed. To establish this the returning line needs to be divided with a three-way manifold. After the three-way manifold a so-called flow restriction valve is needed on both three-way manifold outlets in order to control the hydraulic flow. Due to the fact that it is a parallel circuit the circuit needs to be routed back to the returning line and to avoid the flow to go the opposite direction a check valve is installed to ensure the flow direction.

Three-way manifold

In order to create a parallel circuit two so-called three-way manifolds are needed. Both manifolds need to have one G 1" connection, one G ¾" connection and one G ¼" connection as described in figure 51. This could be accomplished either by buying a manifold which has the right sizes or by using a manifold which has three G 1" connections where the outgoing dimension could be decreased with adapters, figure 51 is illustrated with adapters. Figure 52 shows a rendered 3D-model of such manifold.

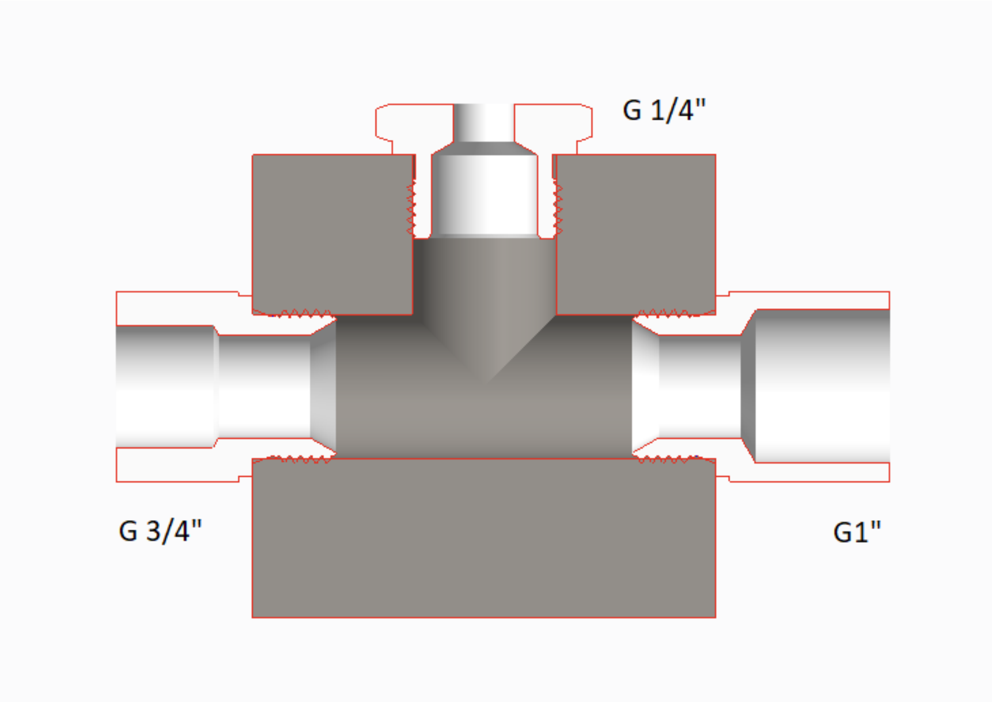

Figure 51, section of an example for a three-way manifold.

Figure 52, 3D rendering of a three-way manifold.

Flow restriction valves

The flow restriction valves have two different sizes. The first size would be G ¾“ which is placed on the outgoing returning line of the three-way manifold. The second size is G ¼“ which is placed on the outgoing parallel line. In combination the restriction valves could decrease and increase the flow in the parallel line to receive desired flow for the particle counter. Normal ball valves which could be manually adjusted could be used, figure 53 shows an example.

Figure 53, example of ball valves which could be used to restrict the flow.

Check valve

The check valve is installed as the last component of the parallel circuit to avoid that the flow goes in the opposite direction than it's desired to do. An example of a check valve is illustrated in figure 54.

Figure 54, example of a check valve.

4.4.3 Humidity sensor & Ferromagnetic sensor

The restrictions of the humidity and the ferromagnetic sensor is that the pressure shall not exceed 20 bar. Since the lubrication system has a pressure relief valve which opens up at 6 bar it is unlikely that the pressure exceeds this. Another important aspect is that the ferromagnetic sensor can't be installed before the particle counter in the flow direction. If that would have been the case it could result in inaccurate readings. Due to the sensor length, both sensors need to be installed in some kind of manifold as illustrated the section view of figure 55. The sizes of the sensors are G ¾" and G 1" which means that the manifold will need to be at least G1" sized with one input, one output and two ports. Figure 56 shows a 3D rendering of the manifold.

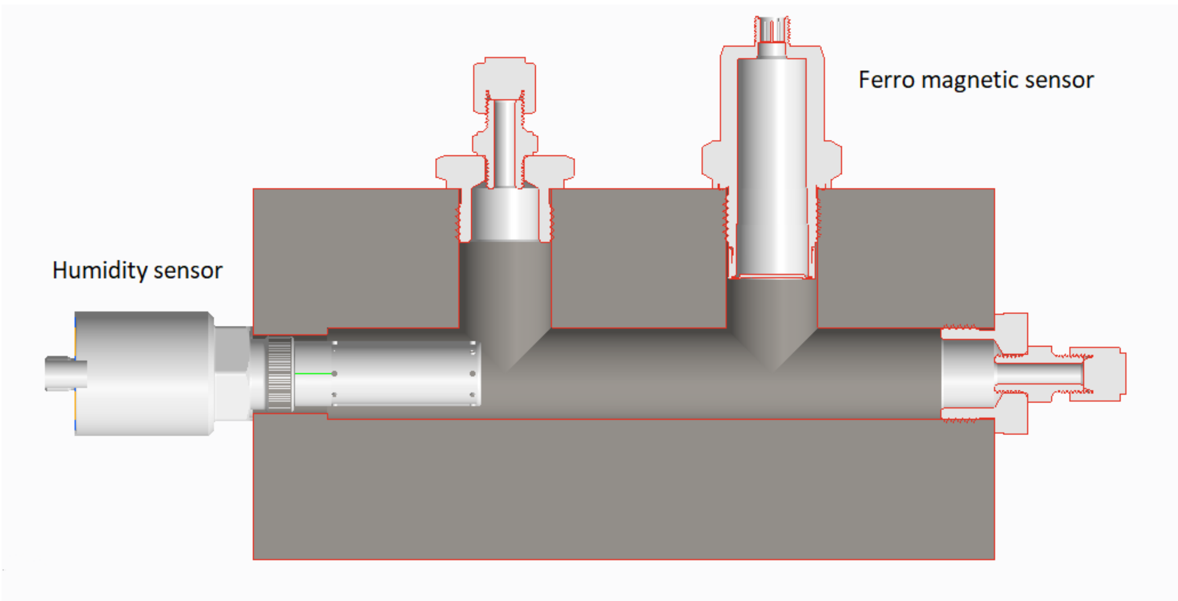

Figure 55, section view of a manifold example.

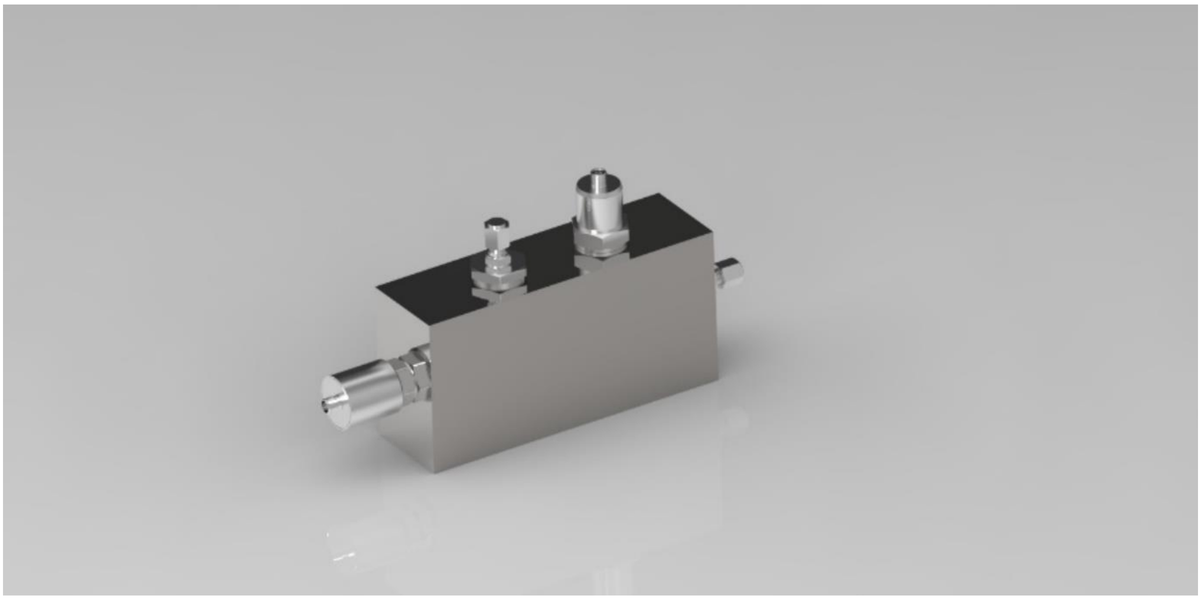

Figure 56, 3D rendering of a manifold example.

4.4.4 Flow sensor

The mindset of the flow sensor is somewhat different than the mindset of the oil analysis sensors. Instead of measuring after the bearings it is of interest to measure the flow before the bearings to ensure that enough flow is provided to the bearings to reduce the wear. Therefore, the flow sensor is placed on the pressure line before the bearing in contrast to all other hydraulic sensors. A 3D-model of the selected sensor is visualized in figure 57.

Figure 57, example of a 3D rendered flow sensor.

4.4.5 Hydraulic system overview

A summarize of the selected components and an idea of their placement is needed to create a hydraulic diagram which then could be used as a reference during the 3D design. An example of how the components could be placed in a hydraulic diagram is illustrated in figure 58.

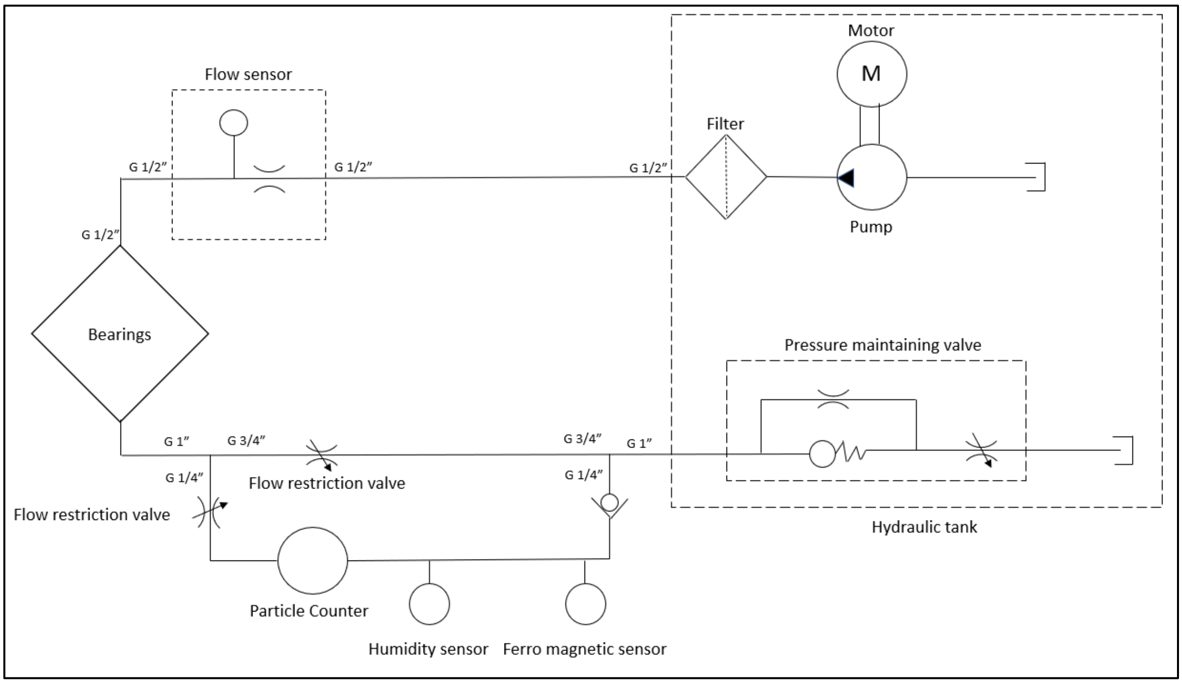

Figure 58, example hydraulic diagram of how components could be placed.

To be able to easily retrofit the condition monitoring system to an existing application the suggested 3D designed is created with pre-assemble and ease installation in mind. All the components but the flow sensor could be mounted on the same board before entering the ship, figure 59. The board is prepared with holes that fits the tank and could therefore be easily and quickly mounted on the tank. An installed board is visualized in figure 59. New 1" hoses might be needed if rerouting the existing hoses becomes difficult. The numbers in figure 60 are translated with table 20.

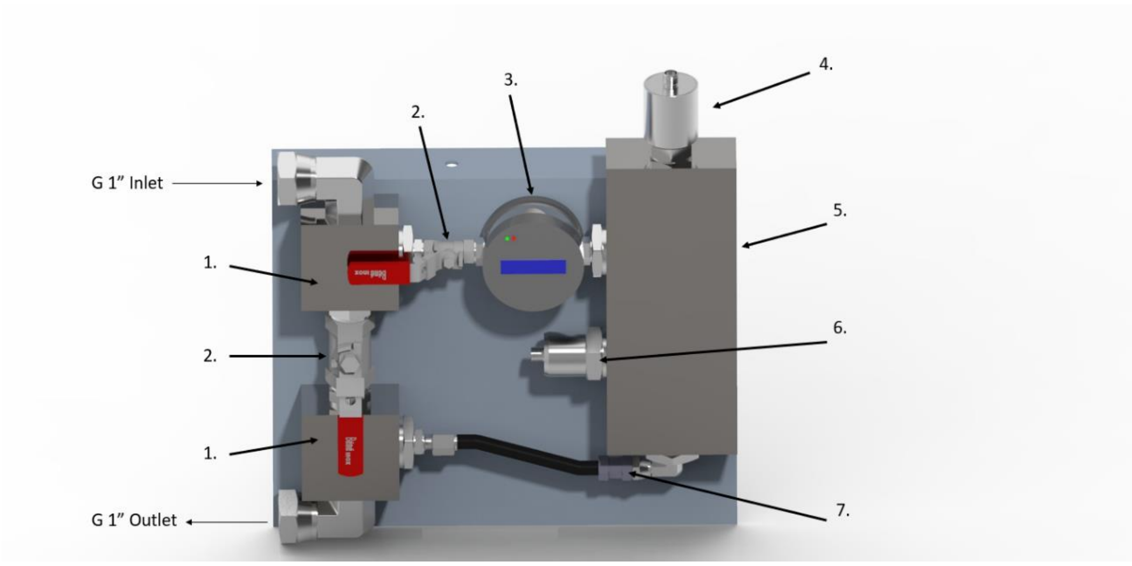

Figure 59, example of a component layout.

Table 20, numbers and explanation for figure 46.

Number	Component
1.	Three-way valve
2.	Flow restriction valve
3.	Particle Counter
4.	Humidity sensor
5.	Sensor manifold
6.	Ferromagnetic sensor
7.	Check valve

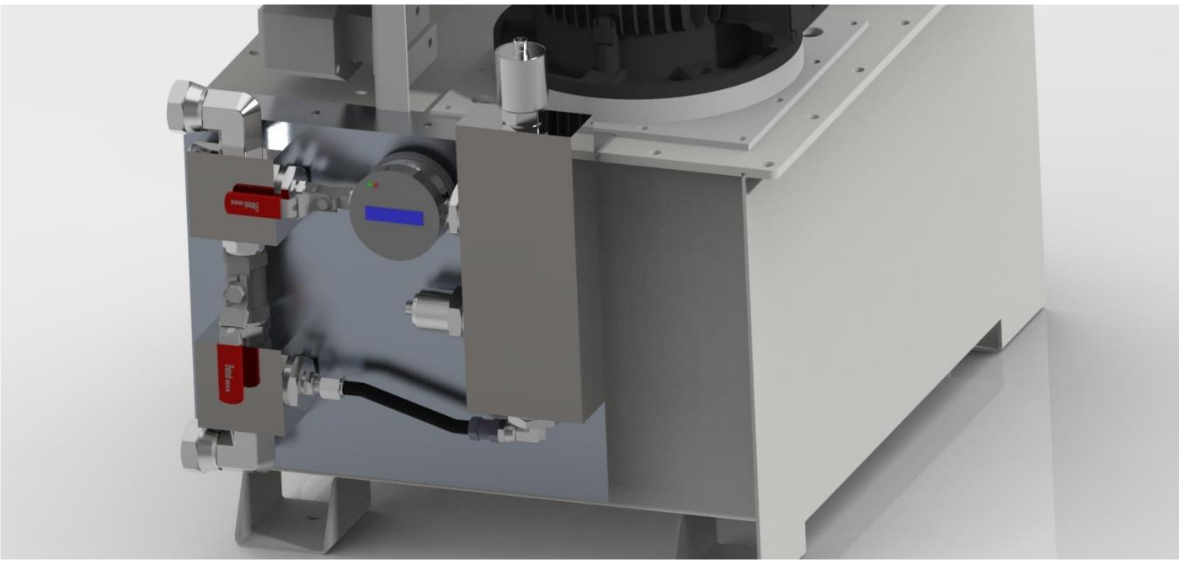

Figure 60, hydraulic power pack and the measuring board.

As for the analysing sensors which already has been described, the flow sensor is placed to ease installation. By using an elbow nipple, the sensor could be installed directly at the tank and the pressure line. The placement is described further in the rendering in figure 61. In figure 61, also the returning line of the tank is illustrated.

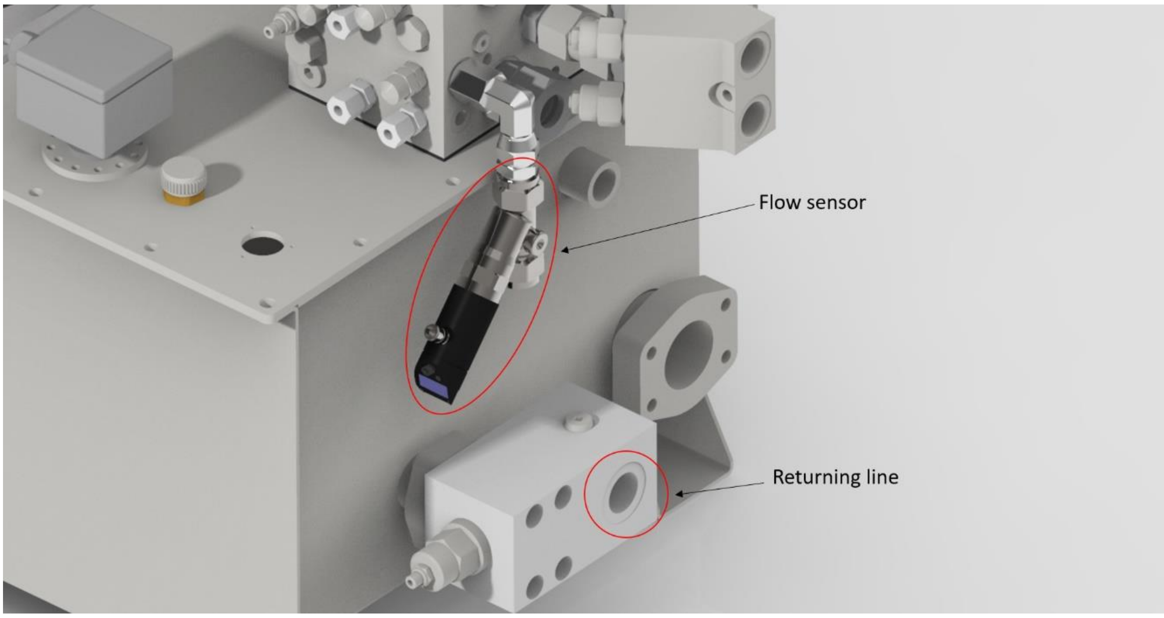

Figure 61, location of flow sensor and returning line.

4.4.6 Torque and RPM sensor

Since all components of the torque sensor is bolted on the existing shaft the sensor could be placed where there is a free spot. Due to the fact that different ships have different shaft lines it could be very difficult to have a specific requirement. However, the torque sensor requires at least 225mm of the shaft in order for the components to be installed and some extra footprint for the stator post. The design of the torque sensor is illustrated without a shaft in figure 62 and with a shaft in figure 63.

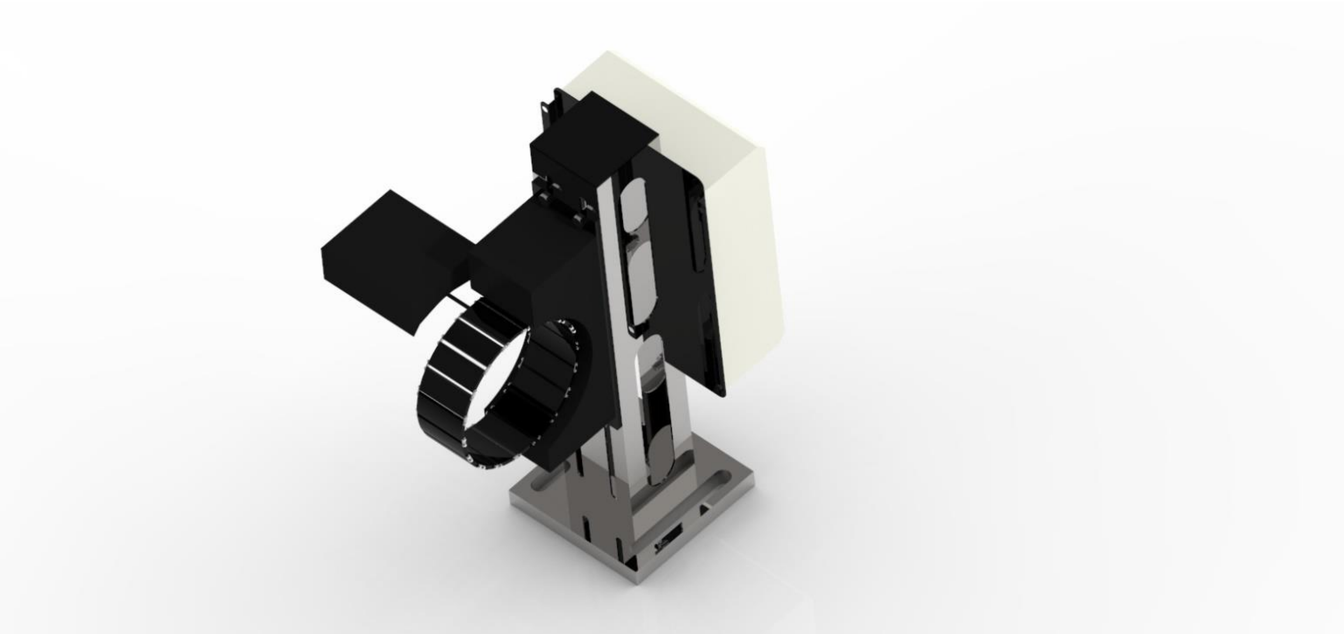

Figure 62, Torque and RPM sensor with shaft hidden.

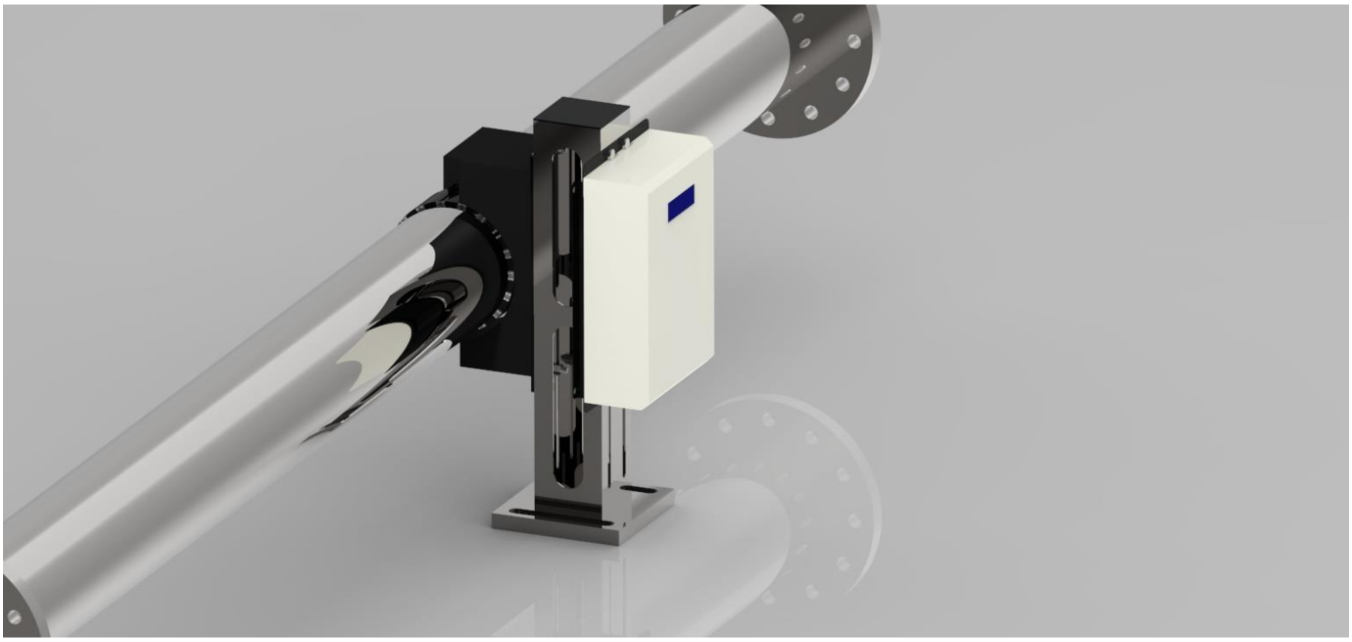

Figure 63, Torque and RPM sensor with a visible shaft.

4.4.7 Vibration sensor

In order to receive the most efficient vibration analysis from a so-called RMS velocity sensor there should be a top mounted and a side mounted sensor. The top mounted sensor reacts to vertical movements while the side mounted sensor reacts to horizontal movements. Figure 64 illustrates a look into a bearing with an axial point of view. However, the number of sensors needed varies with applications. If the shaft lines are long, more bearings might be needed and more bearings means a higher risk of potential functional failures which is why more sensors are needed.

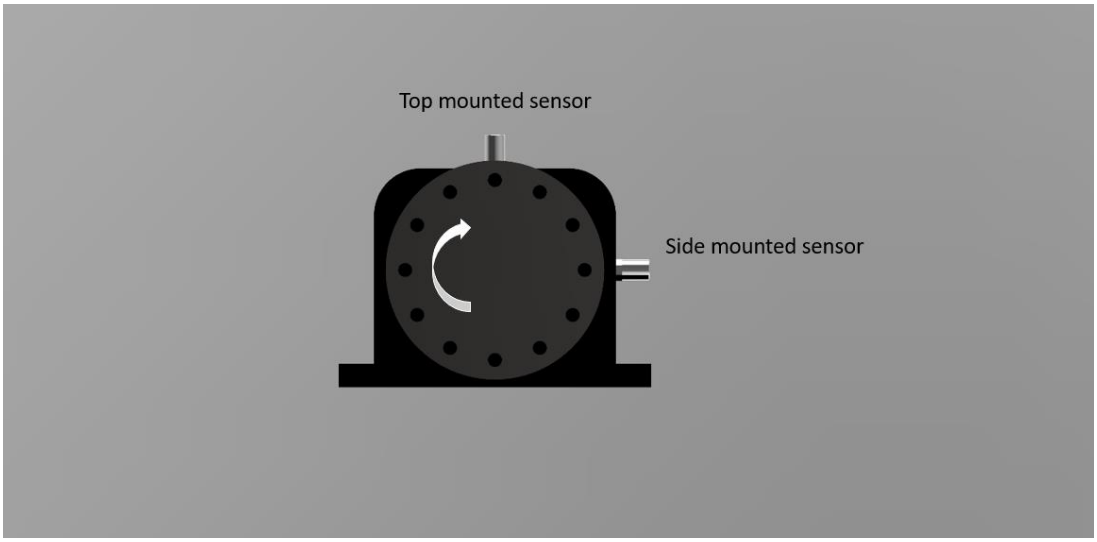

Figure 64, example of vibration sensor placement.

4.5 Estimated costs

The cost estimate is based only on the required components which means that laboured time and costs are not included. The cost will also be based on one component purchase which generally gives a higher price estimate. Discounts could be introduced if the components are bought in bulk which will reduce the price estimate of the system. Also, to be mentioned, is that the torque sensor itself is more expensive than the rest of the system, therefore it is logical to divide the system into two options. The price estimate in table 21 are based on those two options. The first option excludes the torque sensor and the second option includes the torque sensor. The company who offers the selected torque sensor uses a complicated quote where the price is calculated only on real requests. The company could not provide a price estimate for this thesis and therefore the price rather based on experience from other torque sensors price interval, therefore the price estimate should be considered uncertain, it could be less it could be more, most likely less.

Table 21, summarize of the price estimate.

Component	Price per each	Pieces	Total price
Cabinet	≈ 750 SEK	1	≈ 750 SEK
Particle counter	≈ 18 500 SEK	1	≈ 18 500 SEK
Ferromagnetic sensor	≈ 7 500 SEK	1	≈ 7 500 SEK
Humidity sensor	≈ 10 500 SEK	1	≈ 10 500 SEK
Flow sensor	≈ 3 500 SEK	1	≈ 3 500 SEK
Vibration sensor	≈ 3 200 SEK	4	≈ 12 800 SEK
Flow restriction valve	≈ 750 SEK	2	≈ 1 500 SEK
Elbow nipples	≈ 100 SEK	4	≈ 400 SEK
Three-way manifold	≈ 1 500 SEK	2	≈ 3 000 SEK
Hydraulic manifold	≈ 1 500 SEK	1	≈ 1 500 SEK
Straight nipples	≈ 100 SEK	5	≈ 500 SEK
Check valve	≈ 500 SEK	1	≈ 500 SEK
Reducing nipple	≈ 100 SEK	4	≈ 400 SEK
3mm stainless steel plate 350x350mm	≈ 750 SEK	1	≈ 750 SEK
Bolts, nuts and miscellaneous	≈ 1 500 SEK	1	≈ 1 500 SEK
Torque & RPM sensor	≈ 175 000 SEK	1	≈ 175 000 SEK
Total price excl. torque sensor			≈ 63 600 SEK
Total price inc. torque sensor			≈ 238 600 SEK

The estimated price is based on the known components, but some labour needs to be performed to assemble the system. Example of this is the hydraulic board, the electronics in the cabinet and the electronic wires, to mention a few time-consuming operations that needs to be performed. The system will also require further R&D work, for example programming, construction and verification which also should be added to the final estimate. However, by multiplying the total price excl. the torque sensor by a factor of 2 should give a more realistic price. Even after adding the factor the price estimate is still just an indication and a rough estimate which is illustrated in table 22.

Table 22, *summarize of the price estimate including a factor of 2.*

Component	Price per each	Pieces	Total price
Total price excl. torque sensor * 2			≈ 127 200 SEK
(Total price excl. torque sensor * 2) + Price of torque sensor			≈ 302 200 SEK

4.6 Sustainability

4.6.1 Economical perspective

Due to the fact that the developed condition monitoring system is to be seen as an option to the waterjet systems it is critical that the system is price efficient. For example if the price of the optional system is more expensive than the system its designed to monitor, it does not make any sense for the customer to buy the system, instead they could buy a completely new waterjet system cheaper. Setting the price just below the price of the waterjet system does not make any sense either. The price of the system must be set in correlation to the price of the waterjet system. How much extra percent the customer is prepared to invest to receive a more safe and reliable ship is highly individual. In general, the higher the percent the less potential buyers. As a worst-case example the cheapest waterjet system is selected with the most expensive condition monitoring system. By dividing the price of the most expensive condition monitoring system with the price of the cheapest waterjet a worst-case percent of approximately 13% is received which means that a condition monitoring system with a torque sensor costs 13% of the waterjet system. By instead using a condition monitoring system without the torque sensor a percent of approximately 5% is received. Even though 13% is a worst-case scenario it should be considered to be acceptable. If the percent would have been 25-50% the number of potential buyers would have been drastically less. Considering the objectives that was found in ***Section 2.4***, this result should be considered acceptable. Even though the condition monitoring system is an investment it will quickly be repaid and this is important for the potential customer to understand.

4.6.2 Environmental perspective

The second objective from ***Section 2.4*** were that the developed condition monitoring system shall not have a larger impact on the environment than the system its designed to monitor. The CO2 footprint [kg/kg] could be found in the software *EduPack* for most materials. In this thesis most of the materials are either stainless steel or aluminium in combination with small amount of plastic or other materials which either are either not specified or poorly specified. To produce 1 kilogram of stainless steel approximately 5,2kg CO2 is released and to produce 1 kilogram of aluminium approximately 12,4kg CO2 is released. By multiplying the weight of the components with its CO2 footprint, a summarize of the condition monitoring systems total CO2 footprint could be calculated. The weight of all sensors but the torque sensor could be found in corresponding datasheet. To find the weight of the torque sensor the CAD drawings of the stator pole are used to find a volume for the stator pole. The volume is then multiplied with the density of stainless steel which gives a weight of approximately 6kg. This does not include the stator itself, the rotor or the torque cabinet which is why an estimated weight of 15 kg is used. Table 23 states the components and their contribution to the CO2 footprint.

Table 23, overview of weights and contribution to CO2 footprint.

Component	Weight [kg]	Material	CO2 footprint [kg/kg]	CO2 contribution [kg]
Cabinet	2,822	Steel	2,26	6,37
Particle counter	0,72	Stainless steel	5,4	3,88
Ferro magnetic sensor	0,19	Aluminium	12,4	2,35
Humidity sensor	0,14	Aluminium	12,4	1,73
Vibration sensors	0,6	Stainless steel	5,4	3,24
Flow sensor	0,75	Stainless steel	5,4	4,05
Hydraulic board	2,76	Stainless steel	5,4	14,904
Torque sensor	15	Stainless steel	5,4	81
Miscellaneous	5	Stainless steel	5,4	27

To produce the materials which are needed for the condition monitoring system approximately 150kg of CO2 are released into the atmosphere. This amount does not include processing the material, distribution and packaging materials for the products etcetera. If the manufacturing processes were known, also a total footprint could be calculated. However, now that the total weight of released CO2 is known it could be compared to the components it designed to monitor. For example, if water enters the hydraulic system it could lead to cavitation and corrosion which could damage both the hydraulic pump and the cylinders, such fault could lead to replacement of components with an overall weight of at least 300 kg. Let’s say that those components are made of stainless steel and that they need to be replaced during service, this would lead to 10 times higher release of CO2 than the production of a Condition monitoring system itself. Therefore, it could be proven that even though the Condition monitoring system leads to an increased CO2 footprint it could potentially lead to an decrease in CO2 footprint due to the fact that it could indicate a fault before it leads to a functional failure where components need to be replaced.

5 Discussion

5.1 Desires that weren't achieved

5.1.1 Frequency domain analysis

There have been unofficial desires from Kongsberg to have frequency domain vibration analysis as a part of the condition monitoring system but in the end a time domain vibration analysis was selected. The main reason for this is the fact that only 4-20mA signal were to be used. A frequency domain analysis can't be done with 4-20mA signal, other communication and signal protocols could be used but then the work goes beyond the information that was given in the task. The selected method measures tons of data which is analyzed and calculated to an average vibration level that could be communicated with a 4-20mA signal. Frequency domain vibration analysis also measures a ton of data but the data from such sensor is not analyzed or calculated which is why some kind of analyzing controller is needed. The analyzing controller could thereafter communicate the analyzed values to a control unit but due to the amount of data this can't be done with a traditional 4-20mA signal. Also, the amount of data needs to be saved somehow and by performing frequency domain analysis continuously the memory card will be filled fairly quick. However, the selected sensor could be used to start such analysis as an individual system. For example, if the selected sensor reaches a specific average vibration level it gives a start input to an external vibration system where the data could be stored in another control unit. The differences between the methods are that time domain vibration analysis could only communicate that there is a vibration while frequency domain vibration analysis could be used to verify what the vibration comes from, hence, it could be used to understand the vibration further and eventually repair the issue faster. But as stated above, those kind of analysis can't be communicated with a 4-20mA signal, which were an objective of this thesis and therefore it was not further investigated.

5.1.2 Salt and iron measurements

Kongsberg had a desire that the humidity sensor could also measure salt and iron levels in the measured water. The desire had a low prioritization and due to the fact that none of the found sensors could measure salt and iron levels directly this desire was not prioritized neither in the work or the concept selection. However, salt could change the conductivity of the oil, which means that a raising conductivity in the selected sensor could potentially indicate a raising salt level. On the other hand, in order for salt to contaminate the system also water needs to contaminate the system which is also affecting the conductivity, which means that it could be very difficult to verify that the change of conductivity is caused by a raising salt level.

5.1.3 Three axis acceleration sensor

A highly prioritized desire from Kongsberg was that the vibration sensor could measure acceleration in three axis. Such sensors give a so-called sinus wave output signal, which must be analyzed in some kind of control box and translated to a 4-20mA signal which is very difficult or probably impossible to realize. However, as mentioned in ***Subsection 6.1.1***, such sensors could be used in a separated system, which could be activated by the sensor presented in this thesis once a specific average vibration level is reached.

5.2 Potential more parameters that could be measured

One parameters that might be of interest in the future might be oil temperature before and after the bearing and hydraulic pressure before and after the bearing. In general the temperature of a worn bearing increases in the end of its failure and therefore both the vibration and the solid particle parameter should be able to detect the bearing fault before a potential temperature parameter would, but it could still be a good parameter to measure in order to receive a more complete picture of a fault. Also the hydraulic pressure could be interesting to measure before and after the bearing. The designed system only measures the hydraulic flow but the system could provide a flow with a low pressure which could lead to water ingress in the bearing since the bearings are surrounded by water.

5.3 Fulfilment of the project objectives

The main task of this thesis was to develop a conceptional condition monitoring system which could measure a number of different parameters. The project task could be roughly divided into three distinct objectives:

- Define component and system requirements.
- Evaluate and select suitable components.
- Describe and mechanically design a condition monitoring system.

Furthermore, Kongsberg Maritime wanted the thesis to answer the questions *why*, *how* and *where* for each used measuring method.

A so-called requirement specification was used in the thesis to define component and system requirements, which is described in ***Section 3.2***. The concept and the components were evaluated with a so-called Ulrich and Eppinger concept selection process, which is described in ***Section 3.4****.* A description of the selected concepts and their location in the system is described in ***Chapter 4.*** The question *why* is answered in ***Subsection 2.5.5*.** The question *how* is answered in ***Subsection 2.5.6.*** The last question *where* is answered in ***Chapter 4.*** Considering that all of those objectives has been accomplished and documented, it should also be considered that the project has been executed successfully and that all objectives of the project has been fulfilled.

5.4 Potential economical savings by installing a Condition monitoring system

Even though it is an investment to buy a condition monitoring system it could quickly become a huge money saver. The costs could be divided into direct and indirect costs and will be more explained in their own subsection.

5.4.1 Direct costs savings

Condition based maintenance

As per today Kongsberg Maritime uses so-called MTBO (Mean Time Between Overhaulin') which means that for example a bearing is replaced after a certain amount of time or years no matter if the condition of the bearing is good or bad. The positive aspects of a MTBO process are that the repairs could be precisely planned during a drydock for example, but the negative aspects are that components could be replaced even though the condition of the component are good. Service and replacing components of good condition introduces a risks that either the new component is defective or that the new component is incorrectly installed. By instead replacing components based on condition monitoring the components could receive a longer life which is good from an economical perspective and an environmental perspective.

Repairing components before functional failure

By installing a condition monitoring system a failure could be identified and repaired before it reaches a functional failure. Without a monitoring system such faults could be difficult to identify which eventually could lead to a breakdown that could be very expensive. For example, a lubricated bearing fault could lead to contaminations of the oil in the hydraulic system which could cause faults and breakdowns also in the hydraulic system if not addressed immediately. A bearing fault could also cause further mechanical issues which could involve the shaft and other bearings. One fault could therefore lead to several faults which could result in lost income and very expensive repairs, therefore using a condition monitoring system to identify and immediately repair faults could be a huge money saver. It could also lead to a situation where the services could be more carefully planned in comparison with a ship without condition monitoring where a functional failure could come without warnings in the middle of the sea.

5.4.2 Indirect costs savings

A functional failure at sea could not only lead to an expensive repair it could also lead to unsatisfied customers which potentially could lead to a bad reputation. The bad reputation could result in customers to choose another transportation method or another transportation company which will lead to a so-called indirect cost.

5.4.3 Summary

The issues above are hypothetical but they could become very real. All industries are moving towards both a more sustainable and reliable operations due to the fact that there are a lot of money to save by incorporate systems that could evaluate and indicate a functional failure.

5.5 Annual reports from the Condition Monitoring system

Due to the fact that the data is available it could be used as a selling argument. For example, the customer could receive an annual report of the signals with its thresholds. If the signals tend to go towards the threshold, the service team could investigate the reason further during a dry-dock for example. This could lead to a situation where pro-active repairs are done even before the thresholds are exceeded which means that planning service becomes easier and that unplanned services becomes less.

5.6 Fuel reports from the Condition Monitoring system

Another feature that the Condition Monitoring system enables is some kind of fuel saving reports. The feature requires that a torque sensor is used and that a flow sensor is placed on the fuel line. It could lead to a higher understanding of the fuel consumption for the ship owner which could be used to educate the captains to achieve a more fuel-efficient ship. This feature requires more investigations but should be fairly simple to apply.

5.7 Rental and subscription of a condition monitoring system

5.7.1 Rental option

It is understandable that investing in a fairly expensive condition monitoring system could be difficult therefore some kind of rental option might be of interest for the customers. The total cost of the simpler condition monitoring system is 127 200 SEK and the warranty period is 5 years. Dividing the cost by the amount of months gives a monthly fee of approximately 2 100 SEK or an annual fee of 25 500 SEK. The rental option could also allow a more aggressive price setting. For example, if the monthly fee were to be raised to 2 500 SEK the total price would instead be 150 000 SEK which means a larger profit. A selling point could be that the monthly fee is a lot lower than one crew member. This kind of selling method becomes more and more attractive and normalized. The negative part of those kind of selling techniques is that Kongsberg have to bind capital into the condition monitoring systems that they rent and they will need some kind of contract over five years to ensure that the system could be paid. The positive part is when those five years have passed, they receive a passive income where all the income is profit. Let's say that 20 of those systems are still active after 5 years it would lead to a passive income of 50 000 SEK per month.

5.7.2 Subscription option

The subscription option is a combination of the rental option and the annual report. Customer rents the equipment and once a year they receive an annual report of the measured parameters. The report could be used to evaluate if components are to be replaced or if the ship could continue for another year. It could include recommendations from Kongsberg. With this option the monthly fee could be increased to for example 3 000 SEK which gives a total income of 180 000 SEK over 5 years.

5.8 AI implementations

Writing so-called annual reports could become very time consuming for Kongsberg Maritime. Therefore implementation of some kind of AI could be an interesting objective. The AI could collect data from a number of ships and estimate when a potential wear might appear on that specific ship. To do so, the AI first needs to learn how driving behaviors, rotational speed and torque contributes to the wear which means that the AI must analyse data from a ship where an actual wear appeared. Further on, the feedback from the AI could be used directly into the annual report. For example, if it's known that the torque contributes to a raising wear and that specific ship has a higher overall torque than the rest of the fleet it could be a good idea to let the ship owner know that they have a higher applied torque than the rest of the fleet with the same sized waterjet. This information could however be normal due to the specific task that the ship has or due to other reasons, but even the less it could potentially be used to reduce the wear and fuel consumption which is good both from an economical and environmental point of view. The AI could therefore be explained as a comparator between the specific ship and the rest of the fleet and at the same time it could see how certain patterns affects certain parameters.

6 Conclusion

The outcome from the thesis project is a condition monitoring system which could measure a large number of parameters and translate them to a 4-20mA current signal. The signal could be saved with a specific timestamp which enables the possibility to evaluate the parameter over time, with a graph for example. The developed concept system is able to measure the following parameters:

- Shaft torque [kNm].
- Shaft rotational speed [RPM].
- Shaft power [kW].
- Vibration velocity [mm/s].
- Solid particles [p/ml].
- Ferro magnetic particles [s].
- Relative humidity [%].
- Hydraulic oil temperature [°C].
- Hydraulic oil conductivity [pS/m].
- Hydraulic oil relative permittivity [-].
- Lubrication oil flow [l/min].

The layout of the system could depend on which ship it is installed on. The system is designed with so-called retrofit ability in mind, which means that the system could also be installed on existing ships without substantial rebuilds of the ships. Figure 65 shows a typical example of how the system could be installed. Figure 66 show an example of a signal interpreted on a graph in relation to time where all dots are a specific value at a specific time, also known as data.

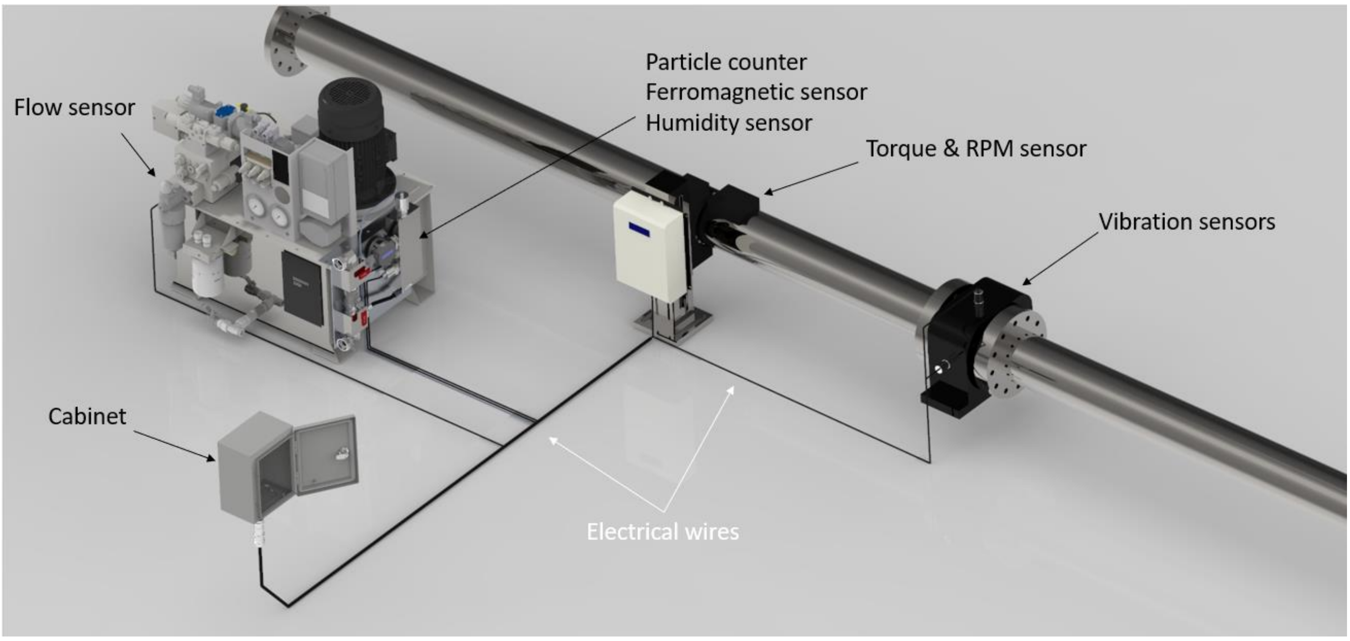

Figure 65, example of a typical system layout.

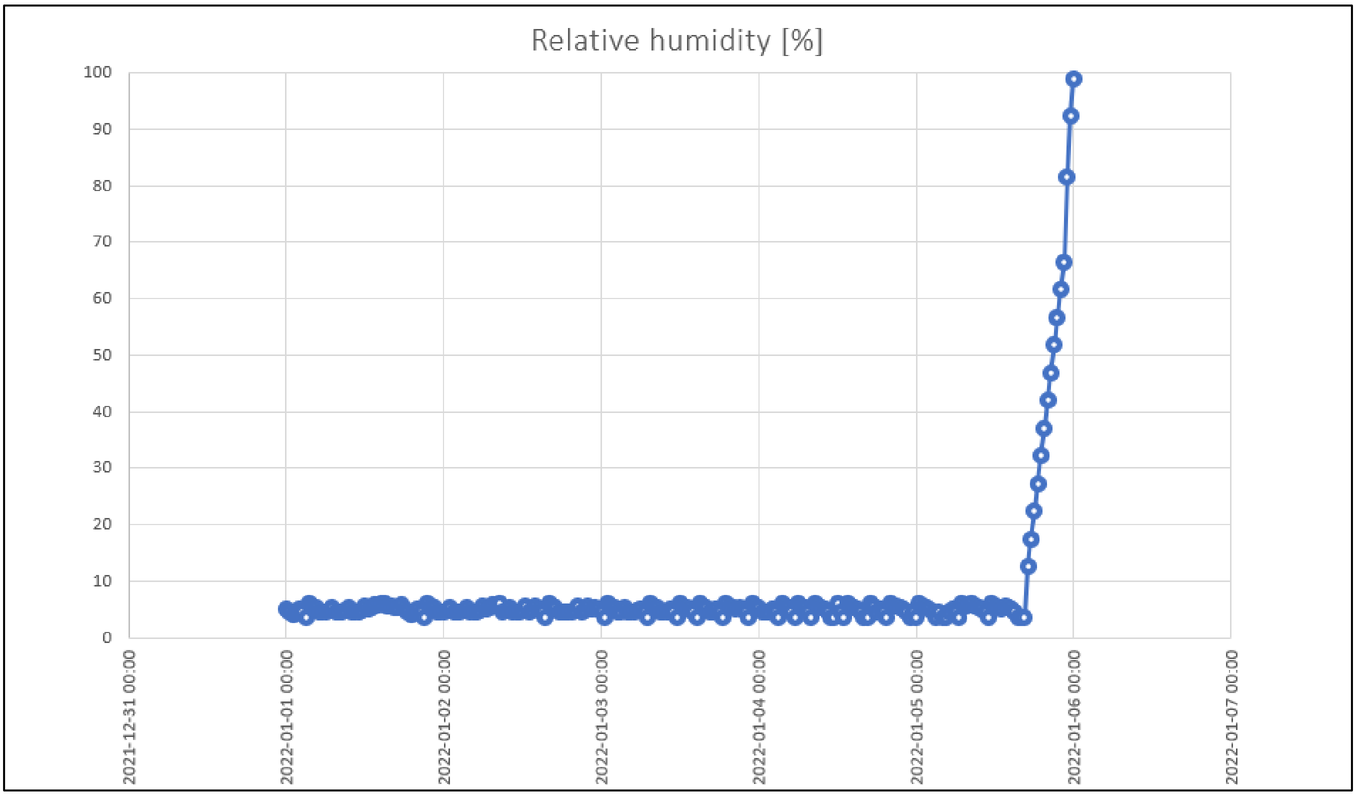

Figure 66, example of an increasing humidity signal over time.

7 Future work

The objective of this thesis was to develop the mechanical part of a condition monitoring system. The thesis should be seen as a concept and therefore it will require further design, verification and testing. In order to receive a functioning condition monitoring system huge amount of programming needs to be accomplished. Programming is critical to translate the selected signal into data and convert the signals into visualized alerts. If the desire to perform frequency domain analysis remains a separated system for this needs to be researched, developed and designed.

References

[1] Design Council. What is the framework for innovation? Design Council´s evolved Double Diamond [Internet]. London: Design Council; 2015 [cited 2022-03-12]. Webpage address: https://www.designcouncil.org.uk/news-opinion/what-framework-innovation-design-councils-evolved-double-diamond

[2] Eriksson M, Lillieskˆld J. Handbok för mindre projekt. 1. uppl. Stockholm: Liber; 2009.

[3] Johannesson H, Persson J, Pettersson D. Produktutveckling: Effektiva metoder för konstruktion och design. 2. uppl. Stockholm: Liber; 2012.

[4] Roorda Niko. Fundamentals of Sustainable Development. 3rd edition. New York: Routledge; 2021.

[5] American Bureau of Shipping (ABS). Equipment Health Monitoring Techniques. [Internet] Spring, US; 2016. [Cited 2022-02-14]. Webpage address: https://ww2.eagle.org/content/dam/eagle/rules-and-guides/current/design_and_analysis/224-GN-EquipCndMonitoring/Equipment_Condition_Monitoring_GN_e.pdf

[6] Watterson James M. Rotating Equipment: Maintenance and Troubleshooting. New York: Momentum Press. 2019. [Cited 2022-02-21] Webpage address: https://search-ebscohost-com.bibproxy.kau.se/login.aspx?direct=true&db=nlebk&AN=2041473&site=ehost-live

[7] Zhang, R, Yu, X, Hu, Y, Zang, H & Shu, W. Active Control of hydraulic oil contamination to extend the service life of aviation hydraulic systems. International Journal of Advanced Manufacturing Technology, vol 96. [Cited 2022-02-28]. Webpage address: https://search-ebscohost-com.bibproxy.kau.se/login.aspx?direct=true&db=aph&AN=129209468&site=ehost-live

[8] Velcon Filters, LLC. ISO 4406:1999 Codes – A three digit code indicating number of particles per milliliter greater than 4, 6, and 14 microns. [Internet] Colorado Springs; 2011. [Cited 2022-05-03] Webpage address: https://promo.parker.com/parkerimages/promosite/Parker%20Velcon/UNITED%20STATES/Technical%20Information/VEL1948-BUL-ISO4406-1999-Fluid-Cleanliness-Information.pdf

[9] Vaisala. Oljefukthaltsbestämning med vattenaktivitetsmätning (aw) [Internet] Finland; Maj 2009. [Cited 2022-05-04] Webpage address: https://www.vaisala.com/sites/default/files/documents/OilMoistureExpressedasWaterActivity_B210806SV-A.pdf

[10] SKF Group. Rolling bearings [Internet] Göteborg; 2018. [Cited 2022-02-29] Webpage address: https://www.skf.com/binaries/pub12/Images/0901d196802809de-Rolling-bearings---17000_1-EN_tcm_12-121486.pdf#cid-121486

[11] Sun J, Wang L, Li F, Li J, Lu H. Online oil debris monitoring of rotating machinery: A detailed review of more than three decades. Mechanical Systems and Signal Processing 149. (2021). [Cited 2022.03.15] Webpage address: https://doi.org/10.1016/j.ymssp.2020.107341

[12] Zhang H, Shi H, Li W, Ma L, Zhao X, Xu Z, Wang C, Xie Y, Zhang Y. A Novel Impedance Micro-Sensor for Metal Debris Monitoring of Hydraulic Oil. *Micromachines*. 2021; 12(2):150. [Cited 2022-02-14] Webpage address: https://mdpi-res.com/micromachines/micromachines-12-00150/article_deploy/micromachines-12-00150-v2.pdf

[13] Tic V, Lovrec D, Edler J. Operation and accuracy of Particle Counters for Online Condition Monitoring of Hydraulics Oils. *Annals of the Faculty of Engineering Hunedoara – International Journal of Engineering.* 2012. [Cited 2022-02-14] Webpage address: https://search-ebscohost-com.bibproxy.kau.se/login.aspx?direct=true&db=aph&AN=102165641&site=ehost-live

[14] Hussain, M.; Hasnain, S. Khan, N.A.; Bano, S.; Zuhra, F.; Ali, M.; Khan, M.; Abbas, N.; Ali, A. Design and Fabrication of a Fast Response Resistive-Type Humidity Sensor Using Polypyrrole (Ppy) Polymer Thin Film Structures. *Polymers.* 2021. [Cited 2022-03-14] Webpage address: https://www.mdpi.com/2073-4360/13/18/3019

[15] Turner, J. D. Automotive sensors. New York: Momentum Press. 2009. [Cited 2022-02-21] Webpage address: https://search-ebscohost-com.bibproxy.kau.se/login.aspx?direct=true&db=nlebk&AN=501117&site=ehost-live

[16] Lang Walter. Sensors and Measurement Systems. Aalborg: River Publishers. (2019). [Cited 2022-02-22] Webpage address: https://search-ebscohost-com.bibproxy.kau.se/login.aspx?direct=true&db=nlebk&AN=2018166&site=ehost-live

[17] Wikipedia. Frequency domain. Webpage address: https://en.wikipedia.org/wiki/Frequency_domain

[18] Technomax middle east ENGG.LCC. Understanding the basics of RMS (Root Mean Square) Frequency in Vibration Analysis. [Internet]. Abu Dhabi; 28 November 2020. [Cited 2022-05-12]. Webpage address: https://www.technomaxme.com/rms-frequency-vibrational-analysis/

[19] Reliability Direct. ISO 10816 Vibration Severity Standards. [Internet] [Cited 2022-05-12] Webpage address: https://www.reliabilitydirectstore.com/articles.asp?id=122

[20] Omega Engineering Inc. Magnetic Flow meters: How they work and what it is [Internet]. Norwalk: 2018 [cited 2022-04-15]. Webpage address: https://www.omega.com/en-us/resources/magmeter

[21] David W. Clarke, Tarek Ghaoud, DWC & TG. (2001). Vortex Flow meter (United States, US09/921,293) Webpage address: https://patents.google.com/patent/WO2002057722A1/en?oq=define:vortex+flowmeter

Appendix A

Requirement Specification Cabinet

	Cell	Criterion	Requirement / Desire	Requirement organisation	Rule reference	Kongsberg reference	Limitation / Function	Classification requirement	Elimination matrix	Relative matrix	Kesselring matrix	Weight for Kesselring (1-5)	Comment
1		Construction											
	1.1	Cabinet are to be made of adequate strenght and rigidity	Requirement	Classification society	(1*)		Function	Yes	X				
	1.2	Enclosure are generally to be made of metal	Desire	Classification society	(2*)		Limitation	No		X	X	4	
	1.3	Cable entrance are not to impair the degree of protection	Requirement	Classification society	(3*)		Function	Yes	X				
	1.4	Screws and nuts inside the cabinet are to be effectively locked.	Requirement	Classification society	(4*)		Function	Yes	X				
	1.5	The cabinet shall have an IP44 class.	Requirement	Classification society	(5*)		Function	Yes	X				
	1.6	If non-aluminium materials are mounted on aluminium, suitable provisions are to be made to prevent galvanic corrosion.	Requirement	Classification society	(6*)		Limitation	Yes	X				
	1.7	Light metal alloys materials such as aluminium are to be avoided as enclosure	Desire	Classification society	(7*)		Limitation	No		X	X	2	1*
	1.8	The cabinet shall have a hinged door	Requirement	Classification society	(8*)		Function	Yes	X				
	1.9	The cabinet shall have a easily operated handle	Requirement	Classification society	(9*)		Function	Yes	X				
2		Placement											
	2.1	Electrical equipment are to be placed so that exposure of water, steam and oil is reduced.	Desire	Classification society	(11*)		Limitation	No				3	
	2.2	If an enclusure is placed where it is likely to be stepped on, it should withstand a the weight of a man.	Requirement	Classification society	(12*)		Function	Yes	X				
3		Enviroment											
	3.1	Components are to be selected with a ambient temperature range of +0°C to +55°C.	Requirement	Kongsberg Maritime	(13*)		Limitation	No	X				4*
	3.2	Components are to be selected with a humidity range of 100% in all temperature ranges.	Requirement	Kongsberg Maritime	(14*)		Limitation	No	X				5*
	3.3	Components are to be made of flame retardant and moisture-resistant materials	Requirement	Classification society	(15*)		Limitation	Yes	X				
	3.4	Electical installations shall be suitable for marine environment.	Requirement	Classification society	(16*)		Limitation	Yes	X				
4		Dimension											
	4.1	The cabinet should fit the control module with the dimensions 128x52*x76mm.	Requirement	Kongsberg Maritime		(17*)	Limitation	No	X				3*
5		General requirements											
	5.1	The price of the cabinet should be as low as possible	Desire	Kongsberg Maritime			Limitation	No		X	X	5	
	5.2	The cabinet should have an easily maneuvered door and locking mekanism	Desire	Kongsberg Maritime			Function	No		X	X	2	
	5.3	The cabinet should be robust from vibrations.	Desire	Kongsberg Maritime			Function	No		X	X	4	
	5.4	The cabinet should be installation flexible and simple	Desire	Kongsberg Maritime			Function	No		X	X	4	
	5.5	The cabinet should be robust from shocks	Desire	Kongsberg Maritime			Function	No		X	X	2	
	5.6	The color of the cabinet should follow Kongsberg color patterns	Desire	Kongsberg Maritime			Function	No		X	X	2	
	5.7	LED Screen with live values from the EHM-system	Desire	Kongsberg Maritime			Function	No		X	X	2	
	5.8	The cabinet should be prepared to be a "Plug N Play" system	Desire	Kongsberg Maritime			Function	No		X	X	3	

Requirement Specification Sensors

	Cell	Criterion	Requirement / Desire	Requirement organisation	Rule reference	Kongsberg reference	Limitation / Function	Classification requirement	Weight for Kesselring (1-5)
1		**Construction criterions from classification**							
	1.1	The components should have a rigid metal enclosure to avoid personel injury if there is a risk	Requirement	Classification society	(1*)		Function	Yes	
	1.2	Components are be constructed to not cause injury when handled in normal manner	Requirement	Classification society	(2*)		Function	Yes	
	1.3	Components are to be constructed so that its function will not be affected by distoration, vibrations and movements from the ship.	Requirement	Classification society	(3*)		Function	Yes	
	1.4	If non-aluminium materials are mounted on aluminium, suitable provisions are to be made to prevent galvanic corrosion.	Requirement	Classification society	(4*)		Function	Yes	
	1.5	In cause of a failure in a component the probability that the failure cause further failures to other components should be acceptably low.	Requirement	Classification society	(5*)		Function	Yes	
	1.6	Equipment shall not cause conduction, induction or radiation malfunction of sorounding components	Requirement	Classification society	(6*)		Function	Yes	
	1.7	Components shall have enough mechanical strenght to withstand the strains it likely to be exposed to when installed	Requirement	Classification society	(7*)		Function	Yes	
	1.8	Enclosures are to be made of steel or other flame retardant materials	Requirement	Classification society	(8*)		Limitation	Yes	
	1.9	Asbestos materials are prohibited	Requirement	Classification society	(9*)		Limitation	Yes	
	1.10	Equipment are to be designated for an IP44 degree of protection	Requirement	Classification society	(10*)		Function	Yes	
2		**Placement requirements from classification**							
	2.1	Components are to be placed so that servicebility is possible and easy.	Requirement	Classification society	(11*)		Function	Yes	
	2.2	Components are to be placed as far as practical so that it is not exposed to water, steam and oil.	Requirement	Classification society	(12*)		Function	Yes	
	2.3	Equipment are to be mounted to not cause or atleast reduce electromagnetic interference.	Requirement	Classification society	(13*)		Function	Yes	
	2.4	If an enclusure is placed where it is likely to be stepped on, it should withstand a the weight of a man.	Requirement	Classification society	(19*)		Function	Yes	
3		**Environmental requirements from classification**							
	3.1	Components are to be selected with a ambient temperature range of +0°C to +55°C.	Requirement	Kongsberg Maritime	(14*)		Limitation	No	
	3.2	Components are to be selected with a humidity range of 100% in all temperature ranges.	Requirement	Kongsberg Maritime	(15*)		Limitation	No	
	3.3	Components are to be made of flame retardant and moisture-resistant materials	Requirement	Classification society	(16*)		Limitation	Yes	
	3.4	Electical installations shall be suitable for marine environment.	Requirement	Classification society	(17*)		Limitation	Yes	
4		**Electrical requirements from classification**							
	4.1	The sensor supply power should be 24V	Requirement	Kongsberg Maritime	(18*)		Limitation	No	
	4.2	The sensor current should be 4-20mA	Requirement	Kongsberg Maritime			Limitation	No	
	4.3	The sensor current should be proportional to the parameter its designed to measure.	Requirement	Kongsberg Maritime			Limitation	No	
5		**General Requirements and desires from Kongsberg**							
	5.1	The cost estimate shall not exceed 150.000 SEK	Desire	Kongsberg Maritime			Limitation	No	5
	5.2	Standard sizes on connections (ON LPP / HPP)	Desire	Kongsberg Maritime			Function	No	4
	5.3	The sensor could measure more parameters	Desire	Kongsberg Maritime			Function	No	2
	5.4	Size of the sensor should be as small as possible	Desire	Kongsberg Maritime			Function	No	4
	5.5	Well known distrubutor	Desire	Kongsberg Maritime			Limitation	No	4
	5.6	Same distrubutor as other sensors	Desire	Kongsberg Maritime			Limitation	No	1
6		**Requirements and desires specific for Solid Particle Sensor**							
	6.1	Interval for small particles > 4um should atleast be 0-20.000 p/ml	Requirement	Kongsberg Maritime			Function	No	
	6.2	Interval for medium particles > 6um should atleast be 0-5000 p/ml	Requirement	Kongsberg Maritime			Function	No	
	6.3	Interval for large particles > 14um should atleast be 0-640 p/ml	Requirement	Kongsberg Maritime			Function	No	
	6.4	Measurement accurancy should be +- 5%	Desire	Kongsberg Maritime			Limitation	No	3
	6.5	Sensor should not have a display which indicates ISO-Values.	Desire	Kongsberg Maritime			Function	No	4
	6.6	Particle analysis (Which kind of material) non-fereous or fereus.	Desire	Kongsberg Maritime			Function	No	5
	6.7	Sample frequence should be atleast once an hour.	Desire	Kongsberg Maritime			Function	No	1
7		**Requirements and desires specific for Humidity Sensor**							
	7.1	Interval should be atleast 0-20000 PPM	Requirement	Kongsberg Maritime			Function	No	
	7.2	Measurement accurancy should be +- 5%	Desire	Kongsberg Maritime			Limitation	No	4
	7.3	Sample frequence should be atleast once an hour.	Desire	Kongsberg Maritime			Function	No	1
	7.4	The sensor should be recalibratable	Desire	Kongsberg Maritime			Limitation	No	4
	7.5	The sensor could measure salt and iron	Desire	Kongsberg Maritime			Function	No	1
8		**Requirements and desires specific for Rotations Speed Sensor**							
	8.1	Interval should be atleast 0-2000 RPM (up to 5000rpm)	Requirement	Kongsberg Maritime			Function	No	
	8.2	Measurement accurancy should be +- 1%	Desire	Kongsberg Maritime			Limitation	No	3
	8.3	Sample frequence should be 10 ms	Desire	Kongsberg Maritime			Function	No	5
	8.4	The sensor assembly should be robust and safe	Desire	Kongsberg Maritime			Function	No	5
9		**Requirements and desires specific for Torque Sensor**							
	9.1	Interval should be 0-3000Nm for sizes 56-90	Requirement	Kongsberg Maritime			Function	No	
	9.2	Interval should be 0-12000Nm for sizes 90-125	Requirement	Kongsberg Maritime			Function	No	
	9.3	Measurement accurancy should be +- 1 %	Desire	Kongsberg Maritime			Limitation	No	4
	9.4	Sample frequence should be once a second	Desire	Kongsberg Maritime			Limitation	No	2
	9.5	The sensor assembly should be robust and safe	Desire	Kongsberg Maritime			Function	No	5
10		**Requirements and desires specific for Vibration Sensor**							
	10.1	Interval should be 50 mm / sek	Requirement	Kongsberg Maritime			Function	No	
	10.3	Measurement accurancy should be +- 5% (?)	Desire	Kongsberg Maritime			Function	No	3
	10.4	Sample frequence should be 10 ms	Desire	Kongsberg Maritime			Limitation	No	4
	10.5	The sensor should measure movement in three axles	Desire	Kongsberg Maritime			Function	No	4
11		**Requirements and desires specific for Flow sensor**							
	11.1	Interval should be atleast 0-20 L/min	Requirement	Kongsberg Maritime			Function		
	11.2	Measurement accurancy should be +- 5%	Desire	Kongsberg Maritime			Limitation		4
	11.3	Sample frequence should be once a second	Desire	Kongsberg Maritime			Limitation		3

Appendix B

Eliminationcriterium:
(+) Yes
(-) No
(?) More info required
(!) Control of requirement specification

Decision:
(+) Proceed solution
(-) Eliminate solution
(?) Seek more information
(!) Control requirement specification

Page 1		Ellimination matrix for cabinet																	
Concept	Product name	Cabinet are made of adequate strenght and rigidity	Cable entrancy does not impair the degree of protection	Components inside the cabinet could be effectively locked	The cabinet has a proctection protection class of atleast IP44	The cabinet is suitable to avoid galvanic corrosion	The cabinet has a hinged door	The cabinet has an easily operated door	The cabinet could be placed so that exposure of water, steam and oil is reduced	The cabinet has enough rigidity so that a human could step on it	The cabinet could withstand an ambient temp between ±0°C and 55°C	The cabinet could withstand a humanity of 100% in all temperature ranges	The cabinet is made of flame retardant materials	The cabinet is made of moisture resistant materials	Components are suited for marine enviroments	The cabinet could fit a control module (128x52x76mm)	Comment	Decision	Link to product
1	**Concept 1**	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+		+	Link
2	**Concept 2**	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+		+	Link
3	**Concept 3**	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+		+	Link
4	**Concept 4**	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+		+	Link
5	**Concept 5**	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	ABS classification	+	Link
																			Link

Eliminationcriterium:
(+) Yes
(-) No
(?) More info required
(!) Control of requirement specification
( ) Does not apply for this application

Decision:
(+) Proceed solution
(-) Eliminate solution
(?) Seek more information
(!) Control requirement specification

Concept	Concept name	Sensor has a rigid metal enclosure if a risk for personal injury is present	Sensor could not injure a person if incorrectly used	The sensor is not affected by distortion, vibration and movements of the ship	The installation of the sensor does not cause galvanic corrosion	Sensor failure does not cause further system failures	Sensor does not cause disturbing conduction, induction or radiation.	The sensor could withstand the strains its likely to be exposed to	Possible enclosure is made of flame retardant materials, such as steel	Asbestos is not used in the sensor	The sensor has a protection degree of atleast IP44	The sensor is installed to ease serviceability	The sensor could be installed to atleast reduce its electromagnetic interference	Possible enclosure is to withstand the weight of a man	The sensor could withstand an ambient temp between ±0°C and 55°C	The sensor could withstand a humanity of 100% in all temperature ranges	The sensor is made of flame retardant materials	The sensor is made of moisture resistant materials	Components are suited for marine enviroments	The sensor power supply should be 24V	The sensor current should be 4-20mA	The sensor current should be proportional to the parameter its designed to monitor	Interval for small particles (>4um) should be 0-20.000 p/ml	Interval for medium particles (>6um) should be 0-5.000 p/ml	Interval for large particles (>14um) should be 0-640 p/ml	Interval should be 0-20.000PPM	Interval should be atleast 0-2.000RPM (up to 5.000RPM)	Interval should be 0-100.000Nm (Sizes 56-100)	Interval should be 0-300.000Nm (Sizes 100-125)	Interval should be 50 mm / sek	Interval should be atleast 0-20 L/min	Comment	Decision	Link to product
Solid particle measurement																																		
1	Concept 1	+	+	+	+	+	+	+	+	+	+	+	+	+	-																		-	Link
2	Concept 2	+	+	+	+	+	+	+	+	+	+	+	+	+	-																		-	Link
3	Concept 3	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+								+	Link
4	Concept 4	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+								+	Link
5	Concept 5	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+								+	Link
6	Concept 6	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+								+	Link
7	Concept 7	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-																	-	Link
8	Concept 8	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-																	-	Link
Material decision sensor																																		
1	Concept 1	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+											+	Link
2	Concept 2	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-																	-	Link
3	Concept 3	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+											+	Link
4																																		Link
5																																		Link
Moisture particle measurement																																		
1	Concept 1	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+					+							+	Link
2	Concept 2	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+					+							+	Link Link
3	Concept 3	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+					+							+	Link
4	Concept 4	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+					+							+	Link
5	Concept 5	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+					+							+	Link
6	Concept 6	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+					+							+	Link
Vibration																																		
1	Concept 1	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+									+			+	Link
2	Concept 2	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+									+			+	Link
3	Concept 3	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+									+			+	Link
4	Concept 4	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+									+			+	Link
5	Concept 5	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+									+			+	Link
6	Concept 6	+	+	+	+	+	+	+	+	+	-																						-	Link
Torque																																		
1	Concept 1	+	+	+	+	?	+	+	+	+	?	+	+	+	?	?	+	+	?	+	+							+	+				-	Link
2	Concept 2	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+							+	+				+	Link
3	Concept 3	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	?	?							+	+				+	Link
4	Concept 4	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+							+	+				+	Link
5	Concept 5	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+							+	+				+	Link
Flow meter sensor																																		
1	Concept 1	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+										+		+	Link
2	Concept 2	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+										+		+	Link
3	Concept 3	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+										+		+	Link
4	Concept 4	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-																	-	Link
5	Concept 5	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+										+		+	Link
6	Concept 6	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+										+		+	Link
7	Concept 7	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+										+		+	Link
8	Concept 8	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+										+		+	Link
9	Concept 9	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+										-		-	Link

Criterium		Cabinet				
		[Ref]. Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
1	Light metal alloys are avoided	0	0	0	0	0
2	Enclosure to be made of metal	0	0	0	0	0
3	The price should be as low as possible	0	0	0	0	0
4	The door is easily maneuvered	0	+	+	+	+
5	The door has a locking mecanism	0	+	0	+	+
6	The cabinet is robust against vibrations	0	0	0	+	0
7	The cabinet is simple and easily installed	0	+	+	+	+
8	The cabinet is robust against shocks	0	0	0	+	0
9	The color of the cabinet follows Kongsberg color palette	0	0	0	+	+
10	The cabinet is prepared to have a LED screen	0	-	-	-	-
11	The cabinet is designed for "Plug N Play" installation	0	0	0	0	0
Sum +		0	3	2	6	4
Sum 0		11	7	8	4	6
Sum -		0	1	1	1	1
Net worth		0	2	1	5	3
Ranking		4	2	3	1	2
Further development		Yes	Yes	Yes	Yes	Yes

Criterium	Solid particle measurement				
	3. [Ref] Concept 3	Concept 4	Concept 5	Concept 6	Concept 7
The cost should be as low as possible	0	0	+	+	+
Connection should be standard sizes	0	0	0	0	0
The sensor could measure more parameters	0	+	+	0	+
Size of the sensor should be as small as possible	0	0	0	0	0
Well known distrubutor	0	0	-	0	0
Same distrubutor as other sensors	0	0	-	+	+
Measurement accurancy should be +- 5%	0	0	0	0	0
Sensor should not have a display which indicates ISO-Values.	0	0	0	0	-
Particle analysis (Which kind of material) non-fereous or fereus.	0	0	0	0	0
Sample frequence should be atleast once an hour.	0	0	+	0	0
Sum +	0	1	3	2	3
Sum 0	10	9	5	8	6
Sum -	0	0	2	0	1
Net worth	0	1	1	2	2
Ranking	3	2	2	1	1
Further investigation					

Criterium	Material measurement	
	1 [Ref]Concept 1	Concept 3
The cost should be as low as possible	0	-
Connection should be standard sizes	0	0
The sensor could measure more parameters	0	0
Size of the sensor should be as small as possible	0	-
Well known distrubutor	0	0
Same distrubutor as other sensors	0	0
Measurement accurancy should be +- 5%	0	0
Sum +	0	0
Sum 0	7	5
Sum -	0	2
Net worth	0	-2
Ranking	1	2
Further investigations		

Criterium	Moisture measurement					
	1 [Ref] Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6
The cost should be as low as possible	0	-	+	+	+	+
Connection should be standard sizes	0	0	0	0	0	0
The sensor could measure more parameters	0	0	-	+	+	+
Size of the sensor should be as small as possible	0	-	+	0	0	0
Well known distrubutor	0	0	+	+	+	+
Same distrubutor as other sensors	0	0	+	+	+	0
Measurement accurancy should be +- 5%	0	0	0	-	-	-
Sample frequence should be atleast once an hour.	0	0	0	0	0	0
The sensor should be recalibratable	0	0	0	0	0	0
The sensor could measure salt and iron	0	0	0	0	0	0
Sum +	0	0	4	4	4	3
Sum 0	10	8	5	5	5	6
Sum -	0	2	1	1	1	1
Net worth	0	-2	3	3	3	2
Ranking	3	4	1	1	1	2
Further development						

Criterium	Vibration measurement				
	1 [Ref] Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
The cost should be as low as possible	0	+	-	0	0
Connection should be standard sizes	0	-	-	0	0
The sensor could measure more parameters	0	0	0	0	0
Size of the sensor should be as small as possible	0	0	-	+	+
Well known distrubutor	0	0	0	0	0
Same distrubutor as other sensors	0	+	+	0	0
Measurement accurancy should be ± 5%	0	+	+	0	0
Sample frequence should be 10ms	0	0	0	0	0
The sensor could measure in three axles	0	0	+	0	0
Sum +	0	3	3	1	1
Sum 0	9	5	3	8	8
Sum -	0	1	3	0	0
Net worth	0	2	0	1	1
Ranking	3	1	3	2	2
Further development					

Criterium	Relative matrix Torque concepts			
	2. [Ref.] Concept 2	Concept 3	Concept 4	Concept 5
The cost should be as low as possible	0	0	0	0
Connection should be standard sizes	0	-	-	+
The sensor could measure more parameters	0	0	0	0
Size of the sensor should be as small as possible	0	-	-	0
Well known distrubutor	0	0	0	0
Same distrubutor as other sensors	0	0	0	0
Measurement accurancy should be +- 1%	0	-	-	-
Sample frequence should be atleast once a second.	0	-	0	0
The sensor assembly should be robust and safe	0	0	0	-
Sum +	0	0	0	1
Sum 0	9	5	6	6
Sum -	0	4	3	2
Net worth	0	-4	-3	-1
Ranking	1	4	3	2
Further development				

Criterium	Flow measurement						
	1 [Ref] Concept 1	Concept 2	Concept 3	Concept 5	Concept 6	Concept 7	Concept 8
The cost should be as low as possible	0	-	0	-	-	0	0
Connection should be standard sizes	0	0	0	0	0	+	0
The sensor could measure more parameters	0	0	0	-	-	0	0
Size of the sensor should be as small as possible	0	0	0	0	0	0	0
Well known distrubutor	0	0	-	0	0	0	0
Same distrubutor as other sensors	0	0	-	0	0	0	0
Measurement accurancy should be +- 5%	0	0	+	0	0	-	-
Sample frequence should be atleast once a second	0	+	+	-	-	+	+
Interval should be atleast 0-20 L/min	0	+	+	0	0	+	+
Sum +	0	2	3	0	0	3	2
Sum 0	9	6	4	6	6	5	6
Sum -	0	1	2	3	3	1	1
Net worth	0	1	1	-3	-3	2	1
Ranking	3	2	2	4	4	1	2
Further development							

Kesselring Cabinet

Issued by:	Date: 2022-04-07	Kongsberg Maritime
Hampus Vinblad		File: Concept selection Kesselring

Criteria:	Target	Weight (W) 1....... 5	Ideal Rating (R) 1 3	Ideal W x R	Ideal Comment (Description of concept 1)	Concept 1 Rating (R) 1 3	Concept 1 W x R	Concept 1 Comment
Light metal alloys are avoided	6	2	3	6		3	6	Steel
Enclosure to be made of metal	12	4	3	12		3	12	Steel
The price should be as low as possible	15	5	3	15		3	15	798SEK incl tax.
The door is easily maneuvered	6	2	3	6		2	4	Must loosen bolts
The door has a locking mecanism	6	2	3	6		2	4	Must loosen bolts
The cabinet is robust against vibrations	12	4	3	12		2	8	Difficult to verify
The cabinet is simple and easily installed	12	4	3	12		3	12	
The cabinet is robust against shocks	6	2	3	6		2	4	Difficult to verify
The color of the cabinet follows Kongsberg color palette	6	2	3	6		2	4	Sand color
The cabinet is prepared to have a LED screen	6	2	3	6		3	6	See through door
The cabinet is designed for "Plug N Play" installation	9	3	3	9		3	9	
	96			96	Good Bad No changed		84	Good Bad No changed
				100,0%	% of full		87,5%	% of full

Criteria:	Concept 2 Rating (R) 1 3	Concept 2 W x R	Concept 2 Comment	Concept 3 Rating (R) 1 3	Concept 3 W x R	Concept 3 Comment
Light metal alloys are avoided	3	6	Metal casing	3	6	Steel
Enclosure to be made of metal	3	12	Metal casing	3	12	Steel
The price should be as low as possible	3	15	812SEK incl tax.	3	15	957SEK incl tax.
The door is easily maneuvered	3	6	Hinges	3	6	Hinges
The door has a locking mecanism	3	6	Key	3	6	Key
The cabinet is robust against vibrations	2	8	Difficult to verify	2	8	Difficult to verify
The cabinet is simple and easily installed	3	12	Includes screws etc	2	8	
The cabinet is robust against shocks	2	4	Difficult to verify	2	4	Difficult to verify
The color of the cabinet follows Kongsberg color palette	2	4	Grey, but not RAL7035	2	4	Sand color
The cabinet is prepared to have a LED screen	1	2	Could be prepared if needed	1	2	Could be prepared if needed
The cabinet is designed for "Plug N Play" installation	3	9	Could be accomplished	3	9	Could be accomplished
		84	Good Bad No changed		80	Good Bad No changed
		87,5%	% of full		83,3%	% of full

Criteria:	Concept 4 Rating (R) 1 3	Concept 4 W x R	Concept 4 Comment	Concept 5 Rating (R) 1 3	Concept 5 W x R	Concept 5 Comment
Light metal alloys are avoided	3	6	Metal casing	3	6	Metal casing
Enclosure to be made of metal	3	12	Metal casing	3	12	Metal casing
The price should be as low as possible	3	15	940SEK incl tax.	2	10	990SEK incl tax.
The door is easily maneuvered	3	6	Hinges	3	6	Hinges
The door has a locking mecanism	3	6	Key	3	6	Key
The cabinet is robust against vibrations	3	12	Approved by DNV-GL	2	8	Difficult to verify
The cabinet is simple and easily installed	2	8	No, installation details included	2	8	Large
The cabinet is robust against shocks	3	6	Approved by DNV-GL	2	4	Difficult to verify
The color of the cabinet follows Kongsberg color palette	3	6	RAL 7035	3	6	RAL 7035
The cabinet is prepared to have a LED screen	2	4	Has a glazed version where a display could be mounted on	1	2	Could be prepared if needed
The cabinet is designed for "Plug N Play" installation	3	9	Could be accomplished	3	9	Could be accomplished
		90	Good Bad No changed		77	Good Bad No changed
		93,8%	% of full		80,2%	% of full

Comments	Concept 1	Comments	Concept 2	Comments	Concept 3	Comments	Concept 4	Comments	Concept 5
Serious distrubutor. Hole in door for a potential display						Serious distrubutor.			

Kesselring evaluation for particle sensor

Issued by:	Date: 2022-04-13	Kongsberg Maritime
Hampus Vinblad		File: Concept selection Kesselring

Criteria:	Target	Weight (W) 1....... 5	Ideal Rating (R) 1 3	Ideal W x R	Ideal Comment (Description of concept 1)	Concept 3 Rating (R) 1 3	Concept 3 W x R	Concept 3 Comment
The cost should be as low as possible	15	5	3	15		2	10	31.831 SEK
Connection should be standard sizes	12	4	3	12		2	8	EO 24 cone end
The sensor could measure more parameters	6	2	3	6		1	2	
Size of the sensor should be as small as possible	12	4	3	12		2	8	114*260*110mm
Well known distrubutor	12	4	3	12		3	12	
Same distrubutor as other sensors	3	1	3	3		3	3	
Measurement accurancy should be +- 5%	9	3	3	9		2	6	±1 ISO code
Sensor should not have a display which indicates ISO-Values.	12	4	3	12		3	12	
Particle analysis (Which kind of material) non-fereous or fereus.	15	5	3	15		1	5	
Sample frequence should be atleast once an hour.	3	1	3	3		3	3	
	99			99	Good Bad No changed		69	Good Bad No changed
				100,0%	% of full		69,7%	% of full

Criteria:	Concept 4 Rating (R) 1 3	Concept 4 W x R	Concept 4 Comment	Concept 5 Rating (R) 1 3	Concept 5 W x R	Concept 5 Comment
The cost should be as low as possible	2	10	35.673 SEK	3	15	Approx. 20.000 SEK
Connection should be standard sizes	2	8	EO 24 cone end	3	12	M16*2 / 1/4" BSP / 7/16" UNF
The sensor could measure more parameters	3	6	Humidity	3	6	Humidity and "Flow"
Size of the sensor should be as small as possible	2	8	114*260*110mm	2	8	102*142*65mm
Well known distrubutor	3	12		2	8	
Same distrubutor as other sensors	3	3		1	1	
Measurement accurancy should be +- 5%	2	6	±1 ISO code	3	9	±1/2 ISO code
Sensor should not have a display which indicates ISO-Values.	3	12		3	12	Could be ordered w/o display
Particle analysis (Which kind of material) non-fereous or fereus.	1	5		1	5	
Sample frequence should be atleast once an hour.	3	3		3	3	
		73	Good Bad No changed		79	Good Bad No changed
		73,7%	% of full		79,8%	% of full

Criteria:	Concept 6 Rating (R) 1 3	Concept 6 W x R	Concept 6 Comment	Concept 7 Rating (R) 1 3	Concept 7 W x R	Concept 7 Comment
The cost should be as low as possible	3	15	18.437SEK or 12360 if more than 50 per year	3	15	
Connection should be standard sizes	2	8	M16*2 / G1/4" BSP	2	8	M16*2
The sensor could measure more parameters	1	2	None	1	2	None
Size of the sensor should be as small as possible	3	12	86*88*52mm	3	12	89*78*51,5mm
Well known distrubutor	3	12		3	12	
Same distrubutor as other sensors	3	3		3	3	Flow meter
Measurement accurancy should be +- 5%	2	6	±1 ISO code	2	6	±1 ISO code
Sensor should not have a display which indicates ISO-Values.	3	12	Without display	1	4	
Particle analysis (Which kind of material) non-fereous or fereus.	1	5		1	5	
Sample frequence should be atleast once an hour.	3	3		3	3	
		78	Good Bad No changed		70	Good Bad No changed
		78,8%	% of full		70,7%	% of full

Comments	Concept 1	Comments	Concept 2	Comments	Concept 3	Comments	Concept 4	Comments	Concept 5
Safe distrubutor but somewhat more expensive then the rest of the products.		Included moisture sensor where the quality most likely is good since the product is labbeled with a well known distrubutor		Built in humidity and flow sensor. Flow sensor measures particle speed and converts it. Experts in filtration.		Has a swedish office which enables more ease further investigations and development		COULD NOT HANDLE 100% HUMIDITY. Could handle 95% approx. But there is an interest since the comany has many product available.	

Kesselring evaluation for material sensor

Issued by:	Date: 2022-04-14	Kongsberg Maritime		Ideal			Concept 1			Concept 3		
Hampus Vinblad		File: Concept selection Kesselring		Description of concept 1								
Criteria:		Target	Weight (W) 1....... 5	Rating (R) 1 3	W x R	Comment	Rating (R) 1 3	W x R	Comment	Rating (R) 1 3	W x R	Comment
The cost should be as low as possible		15	5	3	15		3	15	7.587 SEK or 6180 SEK if 50 or more per year	1	5	149.100 SEK
Connection should be standard sizes		12	4	3	12		2	8	Fairly standard	2	8	Fairly standard
The sensor could measure more parameters		6	2	3	6		1	2	Nope	1	2	Nope
Size of the sensor should be as small as possible		12	4	3	12		3	12	88*Ø35	2	8	150*132*90mm
Well known distrubutor		12	4	3	12		3	12	Yes	3	12	Yes
Same distrubutor as other sensors		3	1	3	3		3	3	Yes	3	3	Potentially
Measurement accurancy should be +- 5%		12	4	3	12		3	12	±5%	1	4	Does not state
		72			72	Good Bad No changed		64	Good Bad No changed		42	Good Bad No changed
					100,0%	% of full		88,9%	% of full		58,3%	% of full

Comments	Concept 1	Comments	Concept 3
More compact and understandable values. Measures the time it takes for the sensor to attract 100% ferreous particles on the lence.		Super expensive sensor which gives unclear values.	

Kesselring evaluation for moisture sensor

Issued by:	Date: 2022-04-13	Kongsberg Maritime		Ideal			Concept 1			Concept 2		
Hampus Vinblad		File: Concept selection Kesselring		Description of concept 1								
Criteria:		Target	Weight (W) 1....... 5	Rating (R) 1 3	W x R	Comment	Rating (R) 1 3	W x R	Comment	Rating (R) 1 3	W x R	Comment
The cost should be as low as possible		15	5	3	15		2	10	12.700 SEK	2	10	Approx. 30.000 SEK
Connection should be standard sizes		12	4	3	12		2	8	NPT 1/2"	2	8	NPT 1/2"
The sensor could measure more parameters		6	2	3	6		3	6	Temp	3	6	Temp
Size of the sensor should be as small as possible		12	4	3	12		2	8	127*Ø33	2	8	77/188*Ø33
Well known distrubutor		12	4	3	12		2	8		3	12	
Same distrubutor as other sensors		3	1	3	3		1	1		1	1	
Measurement accurancy should be +- 5%		12	4	3	12		3	12	±0,02 / 0,03 %	3	12	±0,02 / 0,03 %
Sample frequence should be atleast once an hour.		3	1	3	3		3	3	Ok	3	3	Ok
The sensor should be recalibratable		12	4	3	12		2	8		2	8	
The sensor could measure salt and iron		3	1	3	3		1	1	Cant	1	1	
		90			90	Good Bad No changed		65	Good Bad No changed		69	Good Bad No changed
					100,0%	% of full		72,2%	% of full		76,7%	% of full

Criteria	Concept 3 Rating (R) 1 3	W x R	Comment	Concept 4 Rating (R) 1 3	W x R	Comment
The cost should be as low as possible	3	15	3.842 SEK	3	15	10.620SEK or 6.700SEK if more than 50 per year
Connection should be standard sizes	2	8	EO 24 cone end	2	8	G⅜
The sensor could measure more parameters	1	2	Part of Particle counter	3	6	Yes
Size of the sensor should be as small as possible	3	12	Build in	2	8	137*Ø42
Well known distrubutor	3	12		3	12	
Same distrubutor as other sensors	3	3	Particle counter etc	3	3	Particle counter and ferro sensor
Measurement accurancy should be +- 5%	3	12	±0,2 %	2	8	±3% / ±5%
Sample frequence should be atleast once an hour.	3	3	Ok	3	3	Ok
The sensor should be recalibratable	2	8	Once each 2 years	2	8	
The sensor could measure salt and iron	1	1		1	1	
		76	Good Bad No changed		72	Good Bad No changed
		84,4%	% of full		80,0%	% of full

Criteria	Concept 5 Rating (R) 1 3	W x R	Comment	Concept 6 Rating (R) 1 3	W x R	Comment
The cost should be as low as possible	3	15	5.946 SEK	3	15	9.720 SEK
Connection should be standard sizes	2	8	G⅜	2	8	G⅜
The sensor could measure more parameters	3	6	Temp	3	6	Temp
Size of the sensor should be as small as possible	2	8	97*Ø42	2	8	123*Ø32,3
Well known distrubutor	3	12		3	12	
Same distrubutor as other sensors	3	3	Flow meter etc	1	1	No more concepts
Measurement accurancy should be +- 5%	2	8	±3%	2	8	±3%
Sample frequence should be atleast once an hour.	3	3	Ok	3	3	Ok
The sensor should be recalibratable	2	8		2	8	
The sensor could measure salt and iron	1	1		1	1	
		72	Good Bad No changed		70	Good Bad No changed
		80,0%	% of full		77,8%	% of full

Comments	Concept 1	Comments	Concept 2	Comments	Concept 3	Comments	Concept 4	Comments	Concept 5	Comments	Concept 6
Professional company which want to assist in the development		Product DNV-type approved. Could be ordered w/o display.		Included in particle counter but the producer is large and serious.		Enables further analyses, for example oil aging, contamination with foreign fluids, oil change, oil refreshment and oil mixing.		Relatively cheap product.		Difficult to receive a price estimate.	

Kesselring evaluation for vibration sensor

Issued by:	Date: 2022-04-13	Kongsberg Maritime
Hampus Vinblad		File: Concept selection Kesselring

Criteria:	Target	Weight (W) 1....... 5	Ideal – Description of concept 1: Rating (R) 1 3	Ideal: W x R	Ideal: Comment	Concept 1: Rating (R) 1 3	Concept 1: W x R	Concept 1: Comment
The cost should be as low as possible	15	5	3	15		3	15	3.282 SEK
Connection should be standard sizes	12	4	3	12		3	12	Several options available
The sensor could measure more parameters	6	2	3	6		1	2	
Size of the sensor should be as small as possible	12	4	3	12		2	8	68.58 x Ø28mm
Well known distrubutor	12	4	3	12		2	8	
Same distrubutor as other sensors	3	1	3	3		1	1	
Measurement accurancy should be +- 5%	9	3	3	9		1	3	±10%
Sample frequence should be 10ms	12	4	3	12		3	12	0,2 ms
The sensor could measure in three axles	12	4	3	12		1	4	
	93			93	Good Bad No changed		65	Good Bad No changed
				100,0%	% of full		69,9%	% of full

Criteria:	Concept 2: Rating (R) 1 3	Concept 2: W x R	Concept 2: Comment	Concept 3: Rating (R) 1 3	Concept 3: W x R	Concept 3: Comment
The cost should be as low as possible	3	15	2.736 SEK	1	5	9.407 SEK
Connection should be standard sizes	2	8	1/4 UNF	2	8	1/4 UNF
The sensor could measure more parameters	1	2		1	2	
Size of the sensor should be as small as possible	2	8	63 x Ø22mm	1	4	46 x Ø19mm + Cmodule
Well known distrubutor	3	12		3	12	
Same distrubutor as other sensors	3	3		3	3	
Measurement accurancy should be +- 5%	3	9	±3%	2	6	±5%
Sample frequence should be 10ms	3	12	1ms	3	12	0,1ms
The sensor could measure in three axles	1	4		3	12	With alot of work, yes.
		73	Good Bad No changed		64	Good Bad No changed
		78,5%	% of full		68,8%	% of full

Criteria:	Concept 4: Rating (R) 1 3	Concept 4: W x R	Concept 4: Comment	Concept 5: Rating (R) 1 3	Concept 5: W x R	Concept 5: Comment
The cost should be as low as possible	3	15	3.200 SEK	3	15	most likely around 4k
Connection should be standard sizes	3	12	Several options available	3	12	1/4"-28UNF / M8 × 1.25
The sensor could measure more parameters	1	2		1	2	
Size of the sensor should be as small as possible	3	12	43 x Ø27mm	3	12	50 x Ø 22mm
Well known distrubutor	3	12		2	8	
Same distrubutor as other sensors	1	1		1	1	
Measurement accurancy should be +- 5%	1	3	Does not state %.	2	6	±5%
Sample frequence should be 10ms	3	12	1ms	3	12	1ms
The sensor could measure in three axles	1	4		1	4	
		73	Good Bad No changed		72	Good Bad No changed
		78,5%	% of full		77,4%	% of full

Comments	Concept 1	Comments	Concept 2	Comments	Concept 3	Comments	Concept 4	Comments	Concept 5

Kesselring evaluation for torque sensor

Issued by:	Date: 2022-04-14	Kongsberg Maritime
Hampus Vinblad		File: Concept selection Kesselring

Criteria:	Target	Weight (W) 1....... 5	Ideal – Description of concept 1: Rating (R) 1 3	Ideal: W x R	Ideal: Comment	Concept 2: Rating (R) 1 3	Concept 2: W x R	Concept 2: Comment
The cost should be as low as possible	15	5	3	15		1	5	Price unknown. Built on request
Connection should be standard sizes	12	4	3	12		3	12	70... atleast 1000mm, around shaft.
The sensor could measure more parameters	6	2	3	6		3	6	Speed, power and torque
Size of the sensor should be as small as possible	12	4	3	12		2	8	
Well known distrubutor	12	4	3	12		2	8	
Same distrubutor as other sensors	3	1	3	3		1	1	
Measurement accurancy should be +- 1%	12	4	3	12		3	12	0.1%
Sample frequence should be atleast once a second	6	2	3	6		3	6	10 times per second
The sensor assembly should be robust and safe	15	5	3	15		3	15	
	93			93	Good Bad No changed		73	Good Bad No changed
				100,0%	% of full		78,5%	% of full

Criteria:	Concept 3: Rating (R) 1 3	Concept 3: W x R	Concept 3: Comment	Concept 4: Rating (R) 1 3	Concept 4: W x R	Concept 4: Comment	Concept 5: Rating (R) 1 3	Concept 5: W x R	Concept 5: Comment
The cost should be as low as possible	1	5	Price unknown. Built on request	1	5	Price unknown. Built on request	1	5	Price unknown. Built on request
Connection should be standard sizes	2	8	Sizes unsure, but could most likely more expensive.	2	8	Sizes unsure. No information found	2	8	100.....1000mm, but speed must be below 1000rpm
The sensor could measure more parameters	3	6	Speed, power and torque	3	6	Speed, power and torque	3	6	Speed, power and torque
Size of the sensor should be as small as possible	2	8		2	8		2	8	
Well known distrubutor	2	8		2	8		2	8	
Same distrubutor as other sensors	1	1		1	1		1	1	
Measurement accurancy should be +- 1%	3	12	± 0.25% FSD	2	8	Unsure, most likely ± 0,25%	3	12	± 0,25% FSD
Sample frequence should be atleast once a second	2	4	Unsure, most likely atleast once a second	2	4	Unsure, most likely atleast once a second	2	4	Unsure, most likely atleast once a second
The sensor assembly should be robust and safe	3	15		3	15		3	15	
		67	Good Bad No changed		63	Good Bad No changed		67	Good Bad No changed
		72,0%	% of full		67,7%	% of full		72,0%	% of full

Comments	Concept 3	Comments	Concept 5	Comments	Concept 6	Comments	Concept 7
Strain gauge method		Strain gauge method		Strain gauge method		Optical method Could not handle shaft speeds higher than 1.000 RPM	

Kesselring evaluation for flow sensor

Issued by:	Date: 2022-04-13	Kongsberg Maritime
Hampus Vinblad		File: Concept selection Kesselring

Ideal – Description of concept 1

Criteria:	Target	Weight (W) 1....... 5	Ideal Rating (R) 1 3	Ideal W x R	Ideal Comment
The cost should be as low as possible	15	5	3	15	
Connection should be standard sizes	12	4	3	12	
The sensor could measure more parameters	6	2	3	6	
Size of the sensor should be as small as possible	12	4	3	12	
Well known distrubutor	12	4	3	12	
Same distrubutor as other sensors	3	1	3	3	
Measurement accurancy should be +- 5%	12	4	3	12	
Sample frequence should be atleast once a second	9	3	3	9	
Interval should be atleast 0-25 L/min	12	4	3	12	
	93			93	Good Bad No changed
				100,0%	% of full

Criteria:	Concept 1 Rating (R) 1 3	Concept 1 W x R	Concept 1 Comment	Concept 2 Rating (R) 1 3	Concept 2 W x R	Concept 2 Comment
The cost should be as low as possible	3	15	3.955 SEK	2	10	6.828 SEK
Connection should be standard sizes	3	12	G 1/2 same as pressure line	2	8	G 3/4
The sensor could measure more parameters	2	4	temp	1	2	Nope. Either temp or flow
Size of the sensor should be as small as possible	2	8	110*72*45mm	2	8	110*Ø54mm
Well known distrubutor	3	12		3	12	
Same distrubutor as other sensors	3	3		3	3	
Measurement accurancy should be +- 5%	2	8	±2%	2	8	±2%
Sample frequence should be atleast once a second	1	3	1 sek	3	9	< 0.150 sek
Interval should be atleast 0-25 L/min	1	4	2-40l/min	3	12	0.2...50.0 l/min
		69	Good Bad No changed		72	Good Bad No changed
		74,2%	% of full		77,4%	% of full

Criteria:	Concept 3 Rating (R) 1 3	Concept 3 W x R	Concept 3 Comment	Concept 5 Rating (R) 1 3	Concept 5 W x R	Concept 5 Comment
The cost should be as low as possible	3	15	3.996 SEK	1	5	15.408 SEK
Connection should be standard sizes	1	4	M18	2	8	G¼
The sensor could measure more parameters	2	4	temp	1	2	Nope
Size of the sensor should be as small as possible	2	8	141*Ø34mm	2	8	117*Ø47mm
Well known distrubutor	1	4		3	12	
Same distrubutor as other sensors	1	1		3	3	
Measurement accurancy should be +- 5%	3	12	± 0.2%	2	8	±2%
Sample frequence should be atleast once a second	3	9	< 0.150 sek	1	3	Not defined in datasheet
Interval should be atleast 0-25 L/min	3	12	0.1 ... 25 l/min	2	8	1.2 .... 20.0 l/min
		69	Good Bad No changed		57	Good Bad No changed
		74,2%	% of full		61,3%	% of full

Criteria:	Concept 6 Rating (R) 1 3	Concept 6 W x R	Concept 6 Comment	Concept 7 Rating (R) 1 4	Concept 7 W x R	Concept 7 Comment	Concept 8 Rating (R) 1 5	Concept 8 W x R	Concept 8 Comment
The cost should be as low as possible	1	5	20.497 SEK	3	15	3.489 SEK	3	15	3.862 SEK
Connection should be standard sizes	2	8	G¼	3	12	G 1/2 same as pressure line	2	8	G 3/4
The sensor could measure more parameters	1	2	Nope	2	4	temp	2	4	temp
Size of the sensor should be as small as possible	2	8	117*Ø47mm	2	8	116*147*Ø34mm	2	8	118*147*Ø34mm
Well known distrubutor	3	12		3	12		3	12	
Same distrubutor as other sensors	3	3		3	3		3	3	
Measurement accurancy should be +- 5%	2	8	±2%	1	4	±5%	1	4	±5%
Sample frequence should be atleast once a second	1	3	Not defined in datasheet	3	9	0,1 S	3	9	0,1 S
Interval should be atleast 0-25 L/min	2	8	1.2 .... 20.0 l/min	3	12	0.5 ... 25 l/min	3	12	0.5 ... 25 l/min
		57	Good Bad No changed		79	Good Bad No changed		75	Good Bad No changed
		61,3%	% of full		84,9%	% of full		80,6%	% of full

Comments	Concept 1	Comments	Concept 2	Comments	Concept 3	Comments	Concept 4	Comments	Concept 5	Comments	Concept 6	Comments	Concept 7