Analysis of design requirements for early failure detection in a gear test rig

José Agustín Spaccesi

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Analys av konstruktionskrav för detektering av tidiga kuggskador i en redskapstest rigg

KTH Industriell teknik
och management

José Agustín Spaccesi

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Sammanfattning

Kuggväxlar uppfyller en viktig funktion i många system. I det här arbetet studerades de viktigaste konstruktionskraven hos en tetstrigg för kugg, en FZG-rigg, för att kunna detektera tidiga tecken på kuggskador. Litteraturstudier tillsammans med intervjuer av personer från industrin lade grunden till en jämförelse av produktegenskaper som uppfyller kundkraven med hjälp av en så kallad Quality Function Deployment matrix (QFD-matris). I en QFD omvandlas kundkrav till funktion- och konstruktionskrav, i och med den kunde också de vanligaste kuggskadorna och detekteringsmetoderna kartläggas.

De mest relevanta teknikerna för att detektera tidiga tecken på skador i en FZG-rigg idag visade sig vara en kombination av vibrationsmätningar och akustiska emissionsmätningar. Lösningen är möjlig att implementera. Även andra teknologier finns presenterade i rapporten.

Nyckelord: Konstruktionskrav, Skadedetektering, FZG-rigg, Kuggväxlar

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Abstract

Gears are the heart of many machines, being its function transform and transmit torque. This work is a study of adequate design requirements, in particular, the best methodology to early detect gear fatigue failure using a gear test rig, an FZG test machine. The study used the widely proved QFD analysis technique that introduces the client in the design process by using a matrix system. All available relevant literature on the subject and interviews with relevant people in the field were sources of information for the development of this technique. In that way, a mapping is presented, showing the most common fatigue failure modes and available detection methods.

As a result of the investigation, the most suitable technique for the early gear failure detection in the FZG rig to be a combination of vibration analysis and acoustic emissions analysis, these techniques present the best practice at the moment and also possible to implement. However, other technologies are also presented in the report.

Keywords: Design requirements, Failure detection, FZG test rig, Gear.

KTH Industrial Engineering and Management

Trabajo Final de Máster TRITA-ITM-EX 2020:261

Análisis de requisitos de diseño para detección temprana de fallo en un banco de pruebas de engranajes

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Resumen

Los engranajes son el corazón de muchas máquinas, siendo su función transformar y transmitir par. En este trabajo se realizó un estudio de los requisitos de diseño más adecuados, en particular, la mejor metodología para detección anticipada de fallo a fatiga de engranajes testeados en un banco de pruebas de engranajes FZG. Durante el estudio se utilizó la técnica de análisis QFD que introduce al cliente en el proceso de diseño mediante el uso de un sistema matricial. Toda la literatura relevante disponible sobre el tema, así como entrevistas a personas relevantes en el campo fueron utilizadas como fuente de información para el desarrollo de dicha técnica. También se realizó un mapeo de los diferentes modos y mecanismos de fallo por fatiga más comunes, así como los métodos de detección disponibles.

Como resultado de la investigación se concretó como metodología más adecuada para la detección anticipada de fallo de engranajes en los bancos de prueba FZG, una combinación de análisis de vibraciones y análisis de emisiones acústicas, estas técnicas presentan las mejores características en función de la dificultad de implementación. Sin embargo, en el informe también se presentan otras tecnologías.

Palabras clave: Engranajes, Detección de fallo, Requisitos de diseño, Equipo de prueba FZG.

FOREWORD

I am thankful to my mom, dad, and sister for being my main source of motivation and support, for impulse me every time my speed decreases and for being, even now in the distance, my company through this research.

Thank you to all my friends, who also directly or indirectly have supported me along the path and have helped me with this project. During this project, many things happened, including the COVID-19 global pandemic. This situation made necessary to change the original plan, work from home and contact from distance. I am thankful to the people that kindly find some time to answer my questions during the interviews.

And last but not least, thank you to all the professors who built my knowledge until now, who aroused my sense of curiosity in these topics and who have helped me with its development, especially to my supervisor, Ellen, for her time and dedication.

José Agustín Spaccesi

Stockholm, June 2020

NOMENCLATURE

The notation and abbreviations necessary to understand this work are summarized in this chapter.

Notations

Symbol	***Description***
E	Young´s modulus (Pa)

Abbreviations

UPV	Universitat Politècnica de València
KTH	Kungliga Tekniska Högskolan
FZG	Gear Research Center (Forschungsstelle für Zahnräder und Getriebebau)
QFD	Quality Function Deployment
HOQ	House Of Quality
TUM	Technische Universität München
TFF	Tooth Flank Fracture
TIFF	Tooth Interior Fatigue Fracture
ISO	International Organization for Standardization
RM	Relational Matrix
ML	Machine Learning
CNN	Convolutional Neural Network
AE	Acoustic Emissions

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1 INTRODUCTION

This chapter describes the background, the purpose, the limitations and the methods used in the presented project.

1.1 Background

Gears are rotational machines widely used in industry. Applications of gears include speed, torque and direction power transformation, as well as power transmittance. Better understanding of gears leads to huge improvements in industries of all kinds.

Engineers need to understand the importance of gear design to transmit the necessary torque, supporting the generated stresses, keeping the weight light and the price low. Early detection of failures is valuable in maintenance procedures as well as in the design and manufacture process, helping avoid catastrophic failures and helping in the design validation and in the development of models for predicting gears behavior.

Perusing these goals, the Machine Design department in the *KTH Royal Institute of Technology in Stockholm* has an FZG Gear rig testing machine used for testing gears in efficiency and durability. In particular, testing the durability and detect surface fatigue (or pitting) on gears is a time-consuming task that requires manual works and accurate measurements. The complexity of this process makes the understanding of surface degradation, as well as the realization of new models to predict life in service or the detection of pitting in gear difficult. To solve this problem, the department is planning to buy a new device that makes it easier to detect a failure by measuring metal particles in the lubrication system. On the other hand, there are more ways of detecting a failure, or other indicators of fatigue, for example, by measuring vibrations or acoustic emissions.

1.2 Purpose

The durability test on the FZG rig is a time-consuming task that ballasts investigations (the test process is fully described on the point *2.6 Current durability test*). The analysis of different alternatives, as well as decide which is the best one, are key points in every design process.

The purpose of this project is to evaluate the different methodologies existing for the study and monitoring of fatigue failures in gears, to improve the durability using the FZG rig. The analysis of the methodologies will lead to a recommendation on which one to invest.

1.3 Research questions

Research questions help to focus efforts on the relevant point of investigation and to clarify the objectives of the project. This thesis will focus on the following research questions:

1. Which are the different failure fatigue modes in gears?
2. Which are the different fatigue failure mechanisms on gears?
3. What are the methodologies of early fatigue failure detection on gears?
4. How are fatigue failures detected in the industry today?
5. Which would be the best applicable methodology for early failure detection in the FZG rig?

1.4 Delimitations

Machines are complex systems composed of many different elements. Interactions between components make it difficult only to study individuals. The rig is composed of many components as well, for example, bearings and shafts. Bearings may fail before gears and introduce interferences that will not be considered in this work. In this case, the focus of the study are gears, in particular early detection of fatigue failure on gears.

The project is based on the evaluation of current technologies used for detecting and studying surface transformation on gears. Nevertheless, during the project, no tests will be performed. Results will be obtained by analyzing literature and making interviews with relevant people in the field of gears.

Some failures usually induced by wrong setting-up of the machine are not taken into account.

1.5 Methodology

The methodology used for answering the research questions and reach the objectives of this project is fully explained in the chapter *3 METHODOLOGY*, but the key points are introduced here.

An efficient literature research will be performed to obtain and sort as much useful information as possible and analyze it with a critical and objective point of view. Also, interviews were conducted to receive information from the market and industry.

Finally, with the information obtained from the literature research and the interviews and the understanding of the problem, a Quality Function Deployment (QFD) based methodology, using the House of Quality (HOQ) tool, will be employed to make decisions and sort in between design requirements.

2 FRAME OF REFERENCE

This chapter presents the theoretical reference frame that is necessary for the performed research, design, and understanding of the following work.

2.1 Gears introduction

Gears are mechanical components whose function is to transform and transmit torque. Requirements for its design are getting every time more demanding, rotating at speeds higher than 3.000 rpm, and transmitting forces. The high speed and the applied torque produce on the gear large stresses that eventually cause fatigue failures, making the work of engineers and gear designers extremely important and complex.

Design gears require choosing between different shapes, tooth design, and gear axes configurations, same as take into account loads and ratio requirements, operational conditions, materials, manufacturing processes, and costs.

Gearboxes are machines that, by using gears, transforms power providing speed and torque conversions. Gearboxes are one of the most important applications of gears and principal components of the FZG rig, described on the point *2.5 FZG Gear test rig*.

2.2 Gears in industry

Gears are rotational machines, key points, and one of the most critical components in many industrial machines. Many machines and industries rely on these parts to develop its normal functioning. Improvements and new knowledge in this field are extremely valuables for industrial economies of all kinds.

The *Freedonia Group, Inc.* has calculated that the global gear industry will grow 6.0% annually through 2019 to $221 billion (Freedonia Group Inc, 2015). In particular, in Sweden, many of the biggest companies are directly related to gears. In particular, Volvo, Scania, and many machines used in the mining industry rely on gearboxes to perform its duties and/or make its products.

2.3 Gear nomenclature

For understanding most of the information in this work, some basic gear nomenclature is needed. Many types of gear exit, same as different profile designs, but they all share the main core nomenclature, which is summarized in Figure 1.

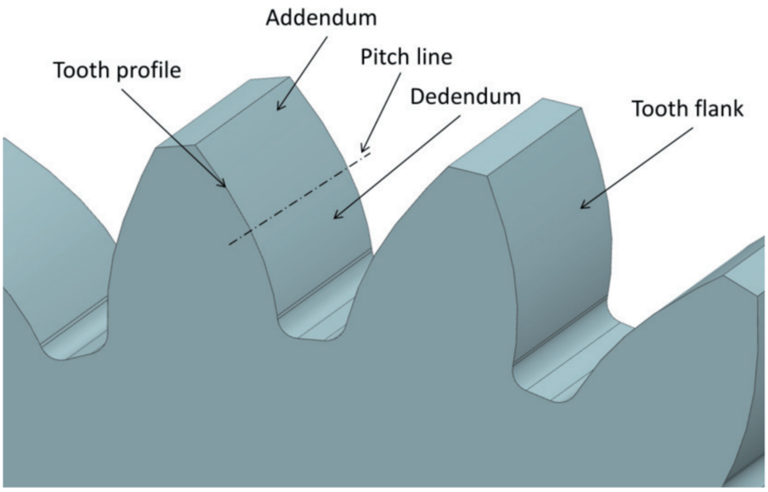


Figure 1. Gear basic nomenclature (Johansson, 2015)

The pitch line is found in the intersection between an imaginary surface, located in the reference line, and the tooth flank. This line fixes the diameter of the gear wheel. The distance between two pitch lines from two adjacent teeth is one pitch. The active tooth flank is the surface that comes into contact with the other gear flank. The tooth root diameter and the area below the pitch is named dedendum and tip diameter, and the area above the pitch is names addendum. Also, the root is the lower part of the dedendum, and the pinion refers typically to the smaller of the gears and usually the one with less teeth.

2.4 Failure modes

Gears, as many other components fail because of two main reasons, because of static loads or because fatigue defects (Figure 2). Later in this chapter, failure mechanisms will be presented. A failure mode can be described as the dominant failure mechanism. A failure mode can also be on a higher function system-level (not just what is taking place between two gear teeth), for example, gear rattle, which is associated with abnormal function or behavior. Failure mechanisms are related to abnormal physical condition or physical state.

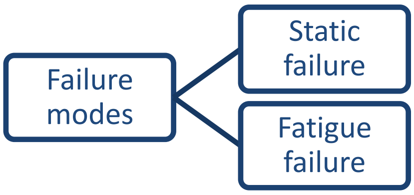


Figure 2. Failure modes classification

Static failure refers to damages that occur in a short space of time, because of a higher load than the one the material can handle. It could mean the permanent deformation of one of the components (in elastic materials) or the sectioning of a component (in hard stiff materials).

Each cycle of load application could produce microcracks or defects in the material. These micro-defects are very small and, most of the time, impossible to be detected, but after every cycle, the chances that this defect grows and finally produce a fail is higher. Any part submits to a load for an extended period will eventually fail because of fatigue.

Design a gear that supplies the static loads is simpler than design for fatigue. Therefore, one talks about the life of the components referring to the approximate number of cycles or time that a part can resist before fail. This project aims to find design requirements that early detect fatigue mode failures.

2.5 FZG Gear test rig

The Gear Research Centre (FZG) is a part of the faculty of Machine Engineering at the Technical University of Munich (TUM). The Institute is focus in the examination and testing of machine elements, such as gears, bearings, synchronizations, and couplings. It is the leading international research institute for gears and transmissions today (Gear Research Centre, n.d.). The Institute developed a machine for testing gear in efficiency and durability, called FZG Gear test rig. This machine is used in industries and investigations related to gears. Figure 3 shows a photo of the rig located on the Machine Design department at KTH.

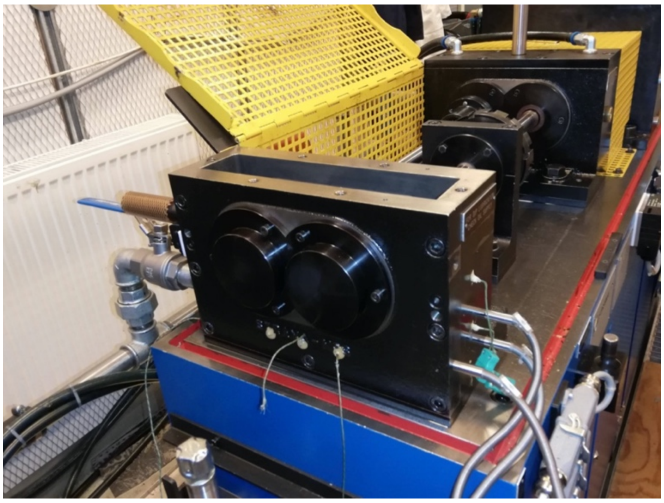
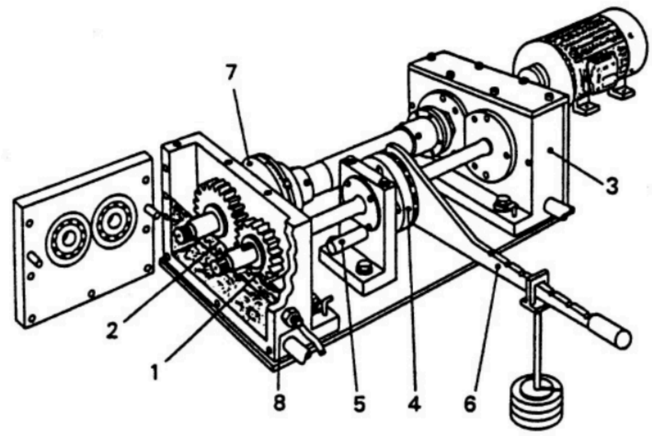


Figure 3. FZG rig on KTH

The machine consists of a power circuit compose of two gearboxes, frictionally engaged by two torque shafts and one electric motor with a speed of 1.500 rpm (Gao, 2015). A clutch provides one of the shafts for load applications (Shaft 1) (Bergseth, 2015). The different parts of the machine are label in Figure 4.



1. Test pinion
2. Test wheel
3. Drive gear case
4. Rotating coupling
5. Locking pin
6. Load lever with weights
7. Torque gauge
8. Temperature sensor

Figure 4. FZG rig draw (Freudenberg Group)

The rig can measure and control some variables. In particular, the temperature in the test gearbox is monitored and controllable to any desirable value. The rig allows speeds from 100 rpm to 3000 rpm in both directions (clockwise and anti-clockwise) so that both gear tooth flanks can be used for testing. The speed and the applied torque inside and outside the power circuit are monitored

(Gao, 2015). Each gearbox has its independent lubrication systems, meaning the oils from each gearbox are not mixed.

Tests in this machine are known for being expensive and time-consuming. Improving the test machine for obtaining more accurate results faster is desirable.

2.6 Current durability test

The current durability test on the FZG rig on KTH consist of placing the test gears on the test gearbox and start running them. After the machine is heated up, the measurements begin. Depending on the material of the testing gears, the applied load, and some other parameters, intervals of cycles are fixed.

In every interval, the machine is stopped, the gearbox opened, and measurements are performed. After visually inspect all teeth, one of the active pinion tooth flanks is cleaned with alcohol and place in position by using a spirit level for being measure with a profilometer, a Taylor Hobson. This is a stylus device able to measure the surface profile of the tooth with high resolution. After one tooth is measured, the same process can be done for all active tooth flanks. By using this data is possible to determine the surface transformation (e.g., how surface asperities are plastically deformed during running) and the damaged area on the tooth. If a pit area in one tooth larger than 5 mm^2 is detected, the test is ended. If it is not, the machine keeps running until 300 hours are reached, then the gear life is assumed to be endless, or the test will last for eternity (Bergstedt, 2019). Note that checking intervals time is not equal. As the test evolves, measurements are made more closely to obtain information as close as possible to the time when the gear fails.

The process is very time-consuming, difficult to perform, requires a lot of human involvement, and the determination of the instant of failure is, at best, an approximation. Improvements in this process are desirable.

2.7 Fatigue failures modes on gears

The predominant fatigue mechanisms are usually defined as the failure mode. The two main fatigue failure modes on gears are contact fatigue and bending fatigue. Contact fatigue refers to the degradation process of the contacting surfaces of the teeth after repeated applications of stress cycles that involve the fall-off of material. Bending fatigue, on the other hand, is due to the whole tooth bends like a beam that eventually break due to fatigue.

On the other hand, bending fatigue is initiated by small microcracks that join together, debilitating the structure and causing the permanent deformation of the tooth. Cracks may happen during the manufacturing process or for usage and, on the contrary of pits, it does not involve a continuous fall-off of material during the growing process. Bending fatigue is more difficult to detect than contact fatigue, and most of the time causes catastrophic failures than end up with severe damages on gearboxes.

To be able to predict or avoid failures (or function degradation), one has to know the mechanisms which take place just before the failure. Several gear failure mechanisms are described in the following next two subchapters. Note that these mechanisms are sometimes also referred to as failure modes.

2.8 Contact fatigue mechanisms on gears

The contact fatigue mechanisms on gears are pitting (or macropitting), micropitting, spalling, and case crushing. Also, pitting can be divided into initial and progressive pitting.

2.8.1 Pitting

Pitting refers to holes or pits in the teeth made because of the fatigue of the material. The contact between components originates micro-cracks close to the surface that grow, causing material detaches, leaving holes on the surface.

Surface deterioration starts when the machine starts rotating. After a short time, as the teeth start entering in contact with each other, some grey marks may appear on the surface as a result of the natural accommodation of surface irregularities. These irregularities usually are imperfections resulted from the manufacturing process. This process is called initial or corrective pitting. It is characterized by small pits in localized areas that can be logically interpreted as high spots due to manufacturing errors, no bigger than 3 μm. These pits (or marks) should not be considered as a reason for failure. The marks will stop growing after the surface is polished or equalized. It is just the result of asperities and high spots on the tooth that act as stress concentration points, after some cycles these small points are gone and the surface is smoother, sometimes leaving the grey marks mentioned above.

Progressive or destructive pitting, on the other hand, are the pits or holes that keep growing even after the surface is equalized. The damage starts typically after a significant amount of compressive stress application cycles. Figure 5 shows a progressive pit hole.

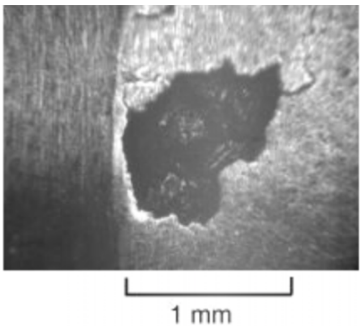


Figure 5. Example of pitting (Baker, 2008)

As pits grow, the effective (or real) area decrease, meaning the area that carries the loads became smaller. At some point, the pitted area is so deep that the tooth cannot take the load, and material breaks out. Pitts initial size and growth speed will depend on the applied load. If the load is high (compare to the endurance of the material), then the pit holes will tend to be big and grow fast, however, if the load is low, the pit holes will be smaller and grow slower.

2.8.2 Micropitting

Micropitting is a fairly new way of failure not covered on ISO 6336 (International Organization for Standardization, 2007) that consist of microscopic fatigue pits on the surface of the tooth. This mode of pitting is mostly found in harden-steel gears used in heavy load applications. Micropitting has the same characteristics as macropitting, but the size usually is ten times smaller, in depths of microns. Micropitting speeds up the deterioration process and increase the chances of cracks to appear, also increasing the risks of a catastrophic fail difficult to detect. Figure 6 shows the appearance of a surface affected by this phenomenon.

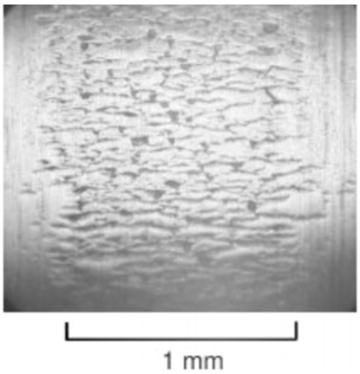


Figure 6. Example of micropitting (Baker, 2008)

2.8.3 Spalling

Pitting is usually a continuous process that starts with small holes that grow as the gears rotate, but sometimes, when the material fatigue occurs under the surface (or on the surface layer when the material is coated), large scales of material fall-off in relatively short time. This failure mode is called spalling and typically starts slightly under the tooth surface in small manufacture defect that grow, causing quite large pieces of steel to fall-off relatively soon in comparison to pitting defects. Figure 7 shows a typical spalling defect. As can be seen, the hole is comparatively bigger.

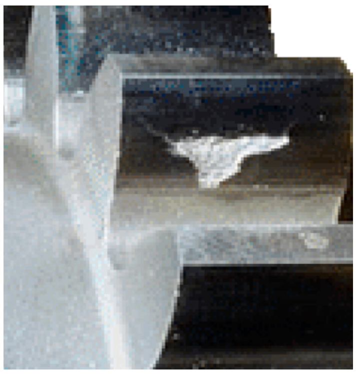


Figure 7. Example of spalling. Modified from (Tobie, 2017)

The difference between spalling and pitting is on the initial size. In contrast, pits are considered to be in depths in the order of 10 μm, spalling is in between 20 μm and 100 μm when they first appear (Yan Ding, 2003).

The same process could happen on coated gears. Large pieces of the coating could fall apart because of abrasion occurred under the coat (in the surface layer), leaving the raw surface of the gears unprotected. This mode of failure is called case crushing, and usually, once the coating is broken, the degradation process speeds up exponentially (Fred K. Geitner, 2012).

2.9 Bending fatigue mechanism on gears

Apart from pits, another fatigue failure reason is cracking. Cracks can happen during the manufacturing process or for usage and, on the contrary of pits, it does not involve a continuous fall-off of material during the growing process.

In gears, because of usage, many small cracks debilitate the structure causing its bending. In normal and good conditions, fatigue breakage requires more oversized loads than surface fatigue. Depending on where the cracks are initiated, different modes of fracture are identified: bending, root breakage, tooth flank fracture, and tooth interior fatigue fracture.

2.9.1 Root breakage

Root tooth breakage is probably the most common fatigue failure mode caused by cracks on gears. Cracks are initiated close to or at the surface, on the low area of the dedendum close to the root of the tooth and evolve from there to the center until the tooth is too weak and breaks. Figure 8 representations the typical appearance of tooth breakage. The arrow shows the loaded flank and the soft grey line the crack grow direction.

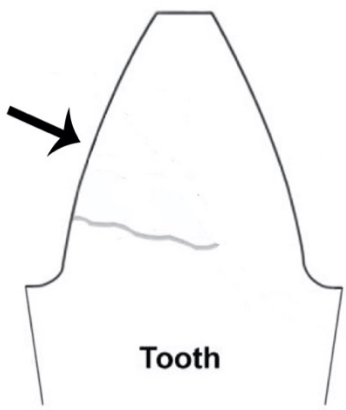


Figure 8. Drawing of the normal appearance of root breakage. Modified from (MackAldener, 2001)

Broken tooth looks there is a missing wedge in the root that goes form the surface to approximately the center. Figure 9 illustrates this fact. On the contrary, as pitting, cracks are deep defects with a small impact on the surface during its growth process, making it very difficult to detect them early.

Figure 9. Root breakage example. Modified from (Tobie, 2017)

2.9.2 Tooth flank fracture (TFF)

Tooth flank fracture (TFF) is a reasonably new failure mode non established on the ISO 6336 (International Organization for Standardization, 2007), like others such as pitting or root breakage. The crack typically is initiated in the loaded flank, under the surface in an approximate depth of the case-core transition.

Literature about it is lacking, but the reason for a tooth to fail because of TFF could be in the material and the location of small manufacture defects. Materials with significantly different Young's modulus (E) between the core and the outside surface trend to have more imperfection and internal stresses in the transition area, which makes more probable cracks to emerge there. (Dipl.-Ing. I. Boiadjiev, 2015). Figure 10 representations a typical TFF fail. The arrow shows the loaded flank, the circle represents the crack origin point and the discontinuous lines, the secondary cracks, very characteristic in this fracture mode. Finally, the soft grey line shows the direction of the final sectioning.

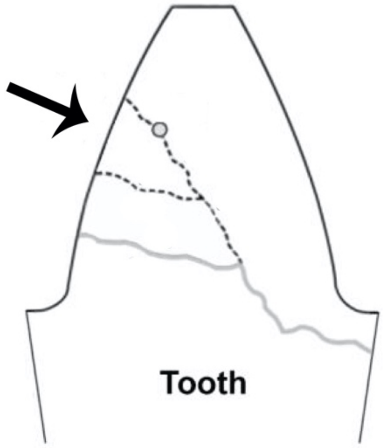


Figure 10. Drawing of the normal appearance of TFF. Modified from (MackAldener, 2001)

Figure 11 shows a tooth that failed because of TFF. The secondary cracks finally merge into a bigger one. The compromised material in between the secondary cracks is missing.

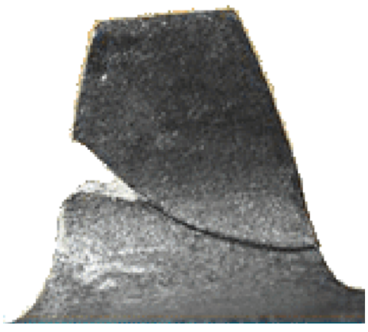


Figure 11. Example of TFF. Modified from (Tobie, 2017)

It is worth it to mention that the failure crack normally is located higher than in the previous case. Unlike root tooth breakage, the tooth is sectioning close to the pitch line.

2.9.3 Tooth interior fatigue fracture (TIFF)

Tooth interior fatigue fracture (TIFF) is a very distinguished failure method in the sense that the crack is initiated in the interior of the tooth, both sides and it breaks in a plane and quite symmetrical shape.

The reasons for the crack initiation in TIFF are the same ones as in TFF. Also, this mode has been observed mostly in gears with higher surface hardnesses. Unlike TFF, this kind of failure has been observed in applications where the teeth are load in two directions, meaning that the both two flanks are loaded during the operation. The crack is initiated the surface-core transition, just like TFF, but there are two cracks origins, one in each flank side. Cracks are symmetrically propagated in the two directions leaving that characteristic plane shape (MackAldener, 2001). Figure 12 is a schematic illustration of TIFF that also shows the starting points of the cracks and the direction of progression and the loaded flanks.

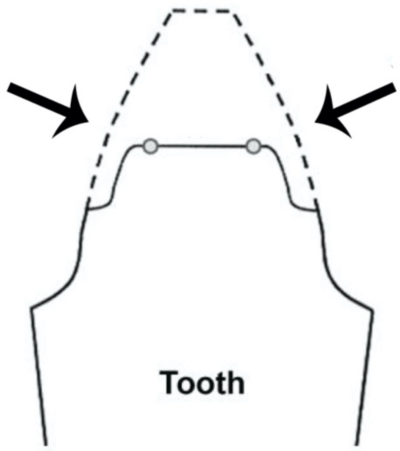


Figure 12. Drawing of the normal appearance of TIFF. Modified from (MackAldener, 2001)

Since the distribution of the load is symmetrical, the cracks are also symmetrical, making the broken profile quite flat. This fact is illustrated in Figure 13 that shows a tooth that failed because of TIFF.

Figure 13. Example of TIFF. Modified from (MackAldener, 2001)

3 METHODOLOGY

In this chapter, the working process is described. The general methodology workflow is presented in the Figure 14. Green represents the sources of information, blue the decision method and red the results.

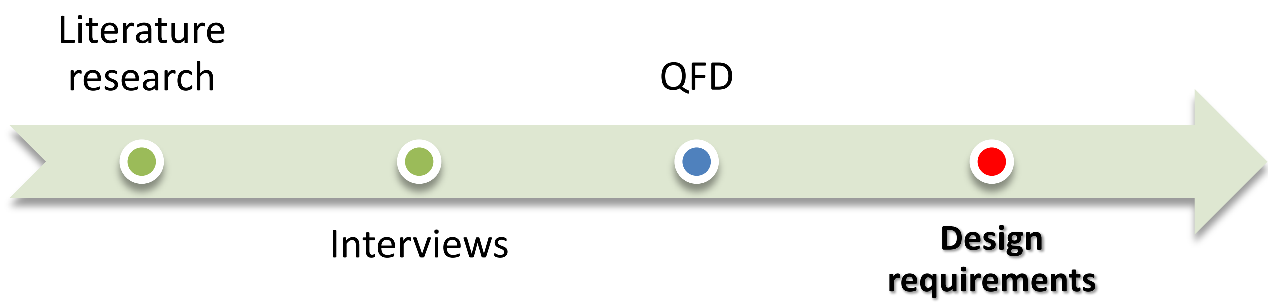


Figure 14. General methodology workflow

3.1 Literature research

A literature research is an investigation performed in a specific field in order to obtain information and knowledge on a certain topic. It is a step to be able to make improvements, allowing the investigator to identify gaps and requirements. The literature research in this project consisted in five phases:

1. Search
2. Evaluate and sort
3. Identify
4. Organize and structure
5. Write

During the first step, many relevant sources of papers and articles were used, being the most suitable the search engines, for example, Google Scholars and Google and the e-magazine, such as GEAR TECHNOLOGY.

However, now a day, the amount of literature accessible on the internet of any imaginable topic is endless, but time and resources are limited. The second phase consisted on the selection, evaluation of the found papers, same as sort them according to the importance they may have. Perusing this objective, and to be as efficient as possible the same as include as many relevant papers, a progressive reading method has been used. Initially, the abstract or summary of many papers and articles was read. After the introduction and/or conclusion of the ones that seem interesting. Finally, only the most interesting ones, according to the last two steps, were read and analyze in deep.

The objective of the literature research is to know the field to be able to make improvements. To reach this goal, three main focus of study were detected (see chapter 2):

- Fatigue failure modes
- Fatigue failure mechanisms
- Early detection methods

As mentioned in Chapter 2, the dominating failure mechanism usually gives the name to the failure mode. Failure mechanisms are also related to abnormal physical condition or physical state, while a failure mode can be on a higher system level.

It was necessary to unify concepts, since different authors may have other names or opinions regarding the same concept.

After unifying, information was addressed thematically, according to the *Research questions* order. The main topic is early detection of fatigue failure, key themes are “fatigue failure modes” and “fatigue indicators and fatigue detection methods”. In the case of “fatigue failure modes”, also two categories have been identified “surface fatigue” and “crack breakage”. On the other hand, inside “fatigue indicators and fatigue detection methods”, methods have been organized by indicators.

Last but not least, the report was written. The writing consisted in the analysis, synthesis and critical evaluation of what has been read and plan in the last steps plus considerations described in the following point.

3.2 Interviews

Interviews with people from the industry in the gear field were performed. These interviews aimed to obtain information on what is being done right now in testing gears, as well as what have been done in the past and what could be done in the future.

During the project, gear testing engineers from the Swedish companies, SCANIA and Höganäs, have been interviewed. The workflow of the applied methodology for obtaining information from the interview is summarized in Figure 15.

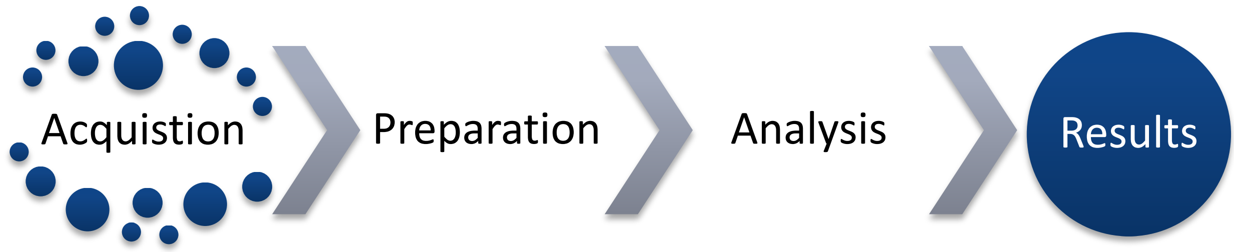


Figure 15. Analysis workflow

The different phases are described in the following points.

3.2.1 Data acquisition

Ask the right questions is vital to obtain answers. The design of the interview and the elaboration of the problem are tasks that need preparation and attention to guaranty a successful interview, obtaining useful information.

The objectives of these interviews were to understand how surface damage is detected in industry. In particular:

- Which are the previous techniques?
- What is used today?
- What could be used in the future?
- What are the relevant indicators?

The chosen interview method was one-on-one, meaning a traditional interview, where there is one person asking and one person answering. The question was almost the same ones in each interview, and are presented in *APPENDIX C*, same as the most relevant answers.

The interview is divided into four parts:

1. Presentation: the objective of the first part is to obtain information of the interviewed person. This information is essential to sort between answers and give the analyzer a context of who is answering the questions.
2. Current situation: questions about the current situation were asked. The idea is to understand what is being measured today, the same as in which testing machine and general results are obtained.
3. Past situation: the orientation is to understand previous devices and processes used in the past to detect surface damage that were replaced with newer and better methods.
4. Future situation: try to obtain the personal view, and opinion of the expert concern to the future of the application plus the orientation that industry is following, same as free comments and observations the expert wants to do.

Interviews were performed via e-mail.

3.2.2 Data preparation and data validation

As not too many interviews were performed, the data preparation was simple, just read and organize the answer according to how and what was the answer.

The validation of the data was not necessary since the experts were chosen carefully. The presentation part of the interview was not analyzed since it was designed with data validation proposes thinking in future studies with more data. Furthermore, this part is not included in *APPENDIX C*.

3.2.3 Analysis method

As data coming from the interview is based on the opinion and experience of people that always involve a certain degree of subjective judgment, it was not possible (or difficult) to apply quantitative analysis methods—the reason why qualitative analysis methods have been applied.

Information obtained from qualitative methods is richer because data used for it also is, but richer in data means variability too, and variability make analysis methods more complex.

In this work, the analysis involved the familiarization with the data and information, the revision of the research objectives and the content analysis of the answers. Meaning that, after reading the information couple of times, the research questions were reviewed. The choosing method for the study was content analysis, commonly used for qualitative data, in particular for responses coming from interviews. Essentially, content analysis means that the information from the interview has been combined with the previous literature research to give the best possible answer to the *Research questions* (Krippendorff, 2018).

3.3 Quality function deployment (QFD) and House of quality (HOQ)

QFD is a methodology that allows the introduction of the client in the design process in a systematic and structured way. QFD must not be confused with HOQ, HOQ is the central tool used in the QFD methodology. Figure 17 explains the QFD process.

In this project, QFD was used in other to make a decision about the different design requirements. Objectives, including the weight importance, have been added according to the conclusions obtained in the research plus previous knowledge, the observation of the rig, and comments from people working with it.

A modified version of the HOQ matrix has been used. Figure 16 shows a schematic draw of it. The proposed HOQ matrix is composed of seven parts:

- Requirements and importance weighting (What?)
- Technical requirements or technical specifications (How?)
- Correlation matrix (How? vs. How?)
- Relationship matrix (RM) (How? vs What?)
- Difficulty (Accomplishment?)
- Technical importance (Result)
- Summary (see equation 1)

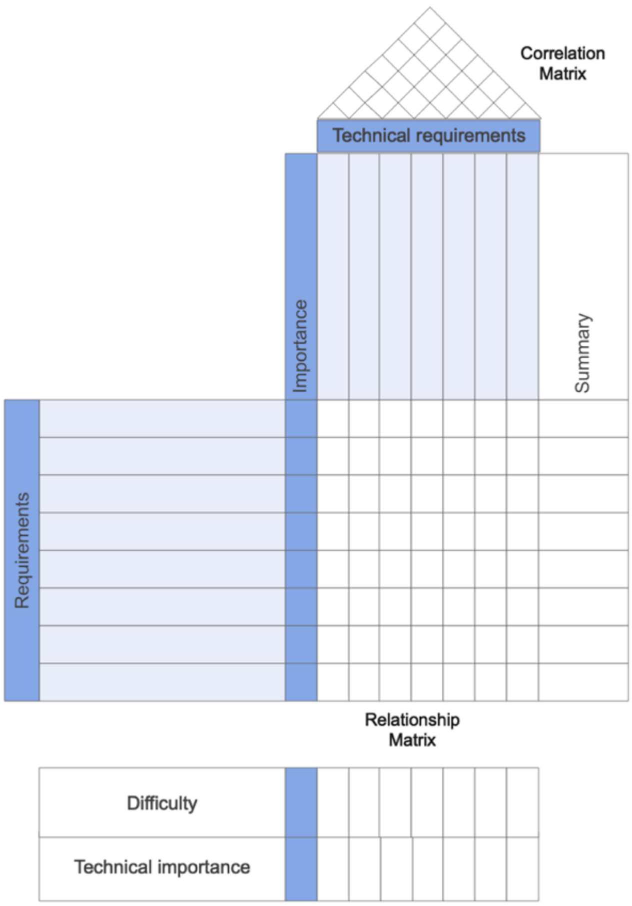


Figure 16. HOQ schematic appearance

In the HOQ, requirements are related to the technical specifications by the Relationship matrix (RM). Requirement represents the voice of the client, and specifications are the possible characteristics of the solution. Values in the RM depends on how strong the relationship between the two is, meaning how affected the requirement is by the specification. Table 1 shows the numerical value of each level of connection. Technical specifications are related by the Correlation matrix.

Table 1. Relationship matrix criteria

No relationship	Weak relationship	Moderate relationship	Strong relationship
0	1	3	9
	▲	○	⊖

Other traditional areas, like competitors were not consider but thinking in the importance of detecting challenges and focus future works and efforts, a *Summary* column was added in order to determine requirements that may not be fulfil by the current technology. This column is calculated by using the *Relationship matrix (RM)* and the *Importance*. According to the equation 1.

$$Summary_i = \frac{Importance\ (\%)_i}{\sum_j (RM_{i,j})} \qquad (1)$$

Columns are represented with “j” and files with “i”. As high this number is, as important future efforts in this particular requirement are. Results are only comparable inside of each HOQ and not in the total method.

The results from each HOQ is used in a new one where the level of abstraction decrease. In this way, the general objectives are transformed into tangible requirements. Advantages of this method include that reduce the developing time, introduce a systematic and structure way to take decisions and collect all available relevant information of the process in one place.

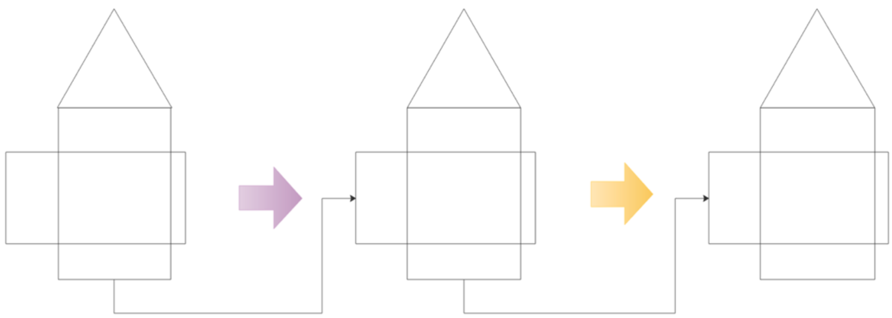


Figure 17. QFD schematic diagram

Many templates for the application of this technique were available. This particular template allows the introduction of all discussed parameter and many more not used in this analysis. The summary column was not possible to add on the template and was calculated apart.

Table 2 summarizes the criteria to set the difficulty of implementation of a particular characteristic. The scale goes from 0 to 10, where 0 is Easy to implement, and 10 is extremely difficult to implement.

Table 2. Difficulty criteria

<table>
<tr><th colspan="2">Value</th><th>Description</th></tr>
<tr><td rowspan="11">Easy to accomplish ⇒ Extremely difficult</td><td>0</td><td>The machine is able to do it by default</td></tr>
<tr><td>1</td><td>Installation of sensors is needed</td></tr>
<tr><td>2</td><td>Small modifications are required</td></tr>
<tr><td>3</td><td>Large modifications are required</td></tr>
<tr><td>4</td><td>Integration of methods and knowledge is required</td></tr>
<tr><td>5</td><td>Small new developments are required</td></tr>
<tr><td>6</td><td>New developments are required</td></tr>
<tr><td>7</td><td>Large developments are required</td></tr>
<tr><td>8</td><td>Modifications and developments are required</td></tr>
<tr><td>9</td><td>Large modifications and developments are required</td></tr>
<tr><td>10</td><td>Everything needs to be developed</td></tr>
</table>

In this chapter, the obtained results from the methods previously described are presented.

4.1 Failure modes and failure mechanisms results

Summarizing, continuing with the classification of Figure 2, Figure 18 shows the classification established in this project for the different fatigue failure modes.

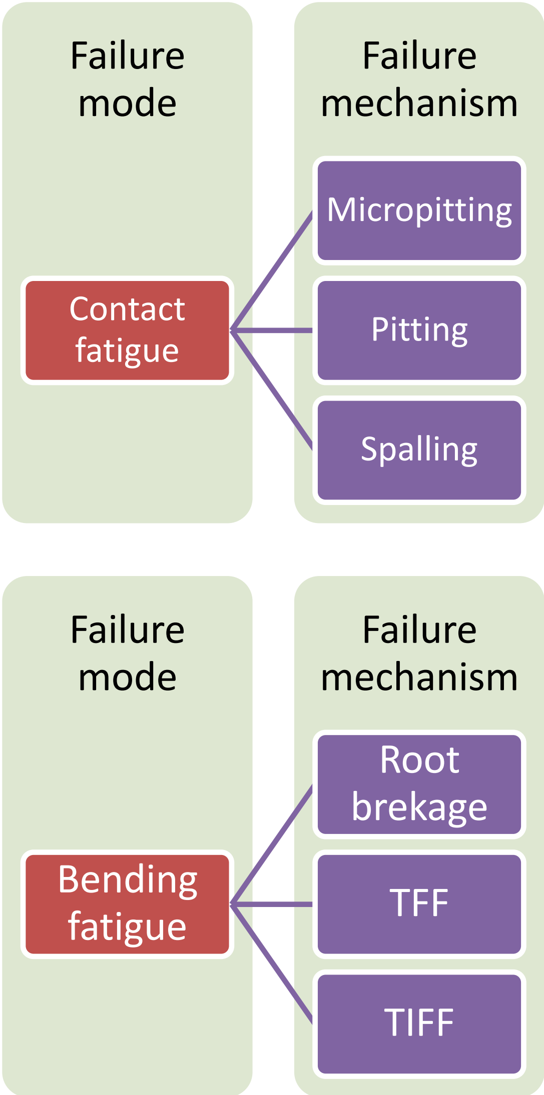


Figure 18. Fatigue failure modes classification

Comparing fatigue failures mechanisms, when they first start, cracks are depth failures with small or no repercussions on the surface, while surface fatigue damages are the opposite. Figure 19 is qualitative graphics that comparatively shows fatigue mechanisms, according to size and depth.

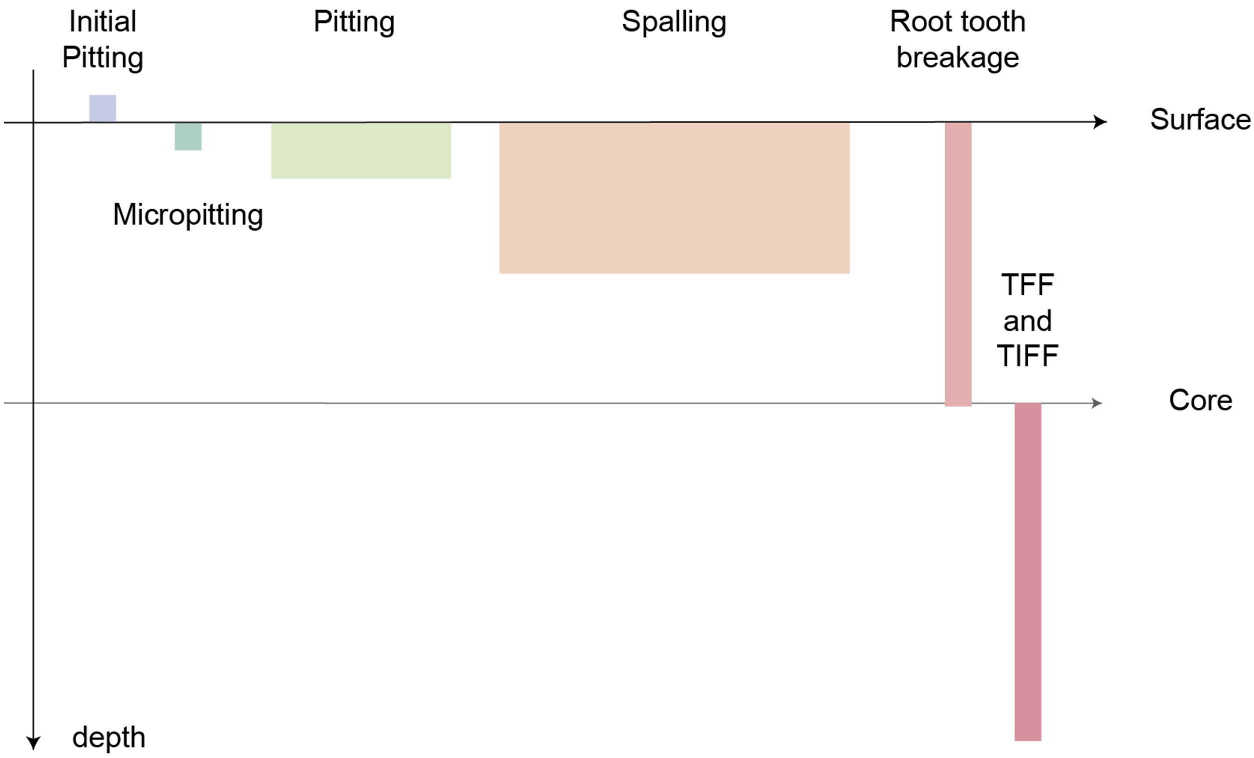


Figure 19. Size and depth comparison of failure mechanisms

4.2 Interview results: early detection in industry

Interviews constituted an important source of information. The results of the interviews are presented in this point.

After reviewing the data from the interviews, it can be concluded that gear systems are complex machines with many components that are related and interconnected. This fact results in companies testing their own products and not the individual components, which means that companies test more often real gearboxes and lest usually just the gears on rig machines.

But that does not mean that gears are not tested individually in rigs. Actually, an important part of the design process of gears is to test them, and even if it can be done in gearboxes, rigs bring a general knowledge that is worth in many applications.

It is also clear that companies develop their own products and not testing systems. That means if it is possible, companies prefer to buy a test system that works then build its own. Developing a new system is expensive and required special skills. If there is not any special interest in it, it does not worth the efforts.

In industry, the most used methodologies for early detect fatigue failure are vibrations and acoustic emissions analysis. By using these two sources of information, it is possible to monitor a wide spectrum of failure mechanisms. Also interesting is that companies are interested in early failure detection methods since catastrophic failures result in the destruction of the all gearbox.

The recommendation of reading about on-line particles was accurate since the methodology proves to minimize visual interventions during the test. Since durability tests are very time-consuming, reduce the number of visible by eye measures will also reduce the test duration.

People that have been working for many years in the gear testing field have seen many gears fail. According to their experience, the main reason for failure on gears that are working in optimal conditions (design conditions) is contact fatigue. Meaning that if there are no manufacturing defects, and the applied load is not higher than the endurance of the material, the piece will fail after many cycles because of surface degradation.

Summarizing,

- Companies mainly test actual gearboxes but also use testing machines, such as the FZG rig
- Industries usually buy testing products and do not develop it owns
- In industry, vibrations and acoustic analysis are the most used methodologies
- Early detection of failure is desirable in the industry
- Visual assessment is required to determine fail
- Minimize the number of visual measurements is desirable
- Gears mostly fail because of contact fatigue

4.3 Early failure detection methodologies analysis

The deterioration of gears is not a silence process, by contrary, it changes the normal behavior of the machine producing alterations that could be measure and analyze to evaluate the current state of the component.

The most promising methodologies nowadays are the following:

- Vibration analysis
- Acoustic emission analysis
- Visual deterioration analysis
- Particles in the lubrication system analysis
- Temperature analysis
- Electrical current analysis

By analyzing expert opinion, same as by listening people working with the FZG rig on KTH, the following important aspects for the chosen methodology were identified.

- Failure mechanisms that may be monitored by this methodology.
    - Micropitting
    - Pitting
    - Spalling
    - Root tooth breakage
    - TIFF or TFF
- The level of modifications that the FZG rig needs.
- If methods for filter interferences or treat the signals are available
- If devices ready to install on the rig are available in the market

During the following points, each methodology is analyzed and summarized into a table showing the most important information and the value that the methodology will have on the Relational Matrix (RM) on the QFD.

4.3.1 Vibration analysis

Many elements produce vibrations during its movements. Vibration is an important indicator not only for gears or gearboxes but also for engines, bearings, pneumatic machines, and many others to analyze its lifetime and proper performance.

The rotational movement of the gears causes vibrations on the gearbox even during normal operation. However, vibrations frequency and amplitude are not the same in new gears than in gears that present deteriorated surfaces. Vibration acceleration increases with the progression of the surface deterioration (Zoltan Korka, 2017).

Measuring and analyzing vibrations is a promising methodology with many advantages. Vibrations are probably the most investigated indicator in the list, tested both in rigs and real gearboxes (Faris Elasha, 2014). Most of the existing investigation about early failure detection rely on this indicator and is used as a comparative method in the development of new methodologies.

The acquisition of data is made by using three-dimensional accelerometers or by laser sensors. Also, measure devices are available in the market, but it needs to be integrated and adapted for the rig machine, giving a RM value equal to 3 in this aspect.

About interferences, it is possible to insulate the vibrations transmitted from other sources, such as the engine, physically by using rubber strips and/or filtering the interferences by measuring the other sources—reasons why the RM value in this aspect has the highest value (9).

All surface damages influence vibrations, but the alterations are more easily detectable when the damage is big. Many improvements in methods have been presented, for example, by using a scalogram. The data derived from the scalogram shows the presence of the fault even when there is only a single pit (Hasan Öztürk, 2008). Also, new modern models made by using ML techniques, in particular deep sparse autoencoder based on dictionary learning, proved to be very robust and showed promising results regarding the influence of working conditions, including loadings and rotating speeds (Yongzhi Qu, 2017). Vibrations analysis is troublesome in the detection of small contact fatigue pit holes, being easier to detect defects when size increase, reasons why RM value is 9 for the detection of pitting and spalling and 1 for micropitting.

Massive efforts have also been invested in the detection of cracks by vibrations. Big entities like NASA has investigated this indicator deeply, even developing its processing methods NA4 and NB4, based on kurtosis normalization of the signal (Leicki, 1996). Cracks detection it was proved in some cases (Meneghetti, 1991) and even by using energy operator that reinforce the signal caused by damage on the gear, some results were archived (Leicki, 1996). Also, there are some available software, such as Adams® and LS-Dyna®, same as simulated models to analyzed vibrations models from gears that provides good results (Scherer, 2012). Nevertheless, studies are not very concluding, the value of RM is bending fatigue mechanisms will be low, 1 in the case of root tooth breakage and 0 for TFF and TIFF. Table 3 gives a summary of the vibration methods characteristics based on the previous text.

Table 3. Vibrations analysis summary

		RM
Failure mechanisms	Monitor micropitting	1
	Monitor pitting	9
	Monitor spalling	9
	Monitor root tooth breakage	1
	Monitor TFF and TIFF	0
Level of modification needed		9
Interferences filtering		9
Availability of devices on the market		3

The difficulty of the implementation according to Table 2 ranks in 2, since modifications are required.

4.3.2 Acoustic emission analysis

Acoustic emissions (AE) are transient elastic waves that result from a sudden strain energy release within a material due to the occurrence of microstructural changes.

Surface degradation increases friction, increasing also the noise, by measuring AE is possible to evaluate the surface degradation status. Also, microstructural changes, like cracks formation and cracks propagation, are possibly detected by this method.

This methodology is inspired by the real world. In the actual gearboxes, people working with them know when something is wrong because of the noise that gears do when the machine is not working correctly. When noises are different from its normal behavior, they know something is going wrong, so the machine is stopped and fixed it.

Measure AE is more complicated than vibrations because noise is everywhere, and most of the time is just not possible to isolate the machine or insulate the room enough to avoid other sounds. A possible solution is measuring the sources of interferences and filter the signal, but removing all the noise from the signal is not possible, the reason why RM value for interferences is equal to 3.

AE sensors are better than accelerometers in the detection of higher frequencies, which make easier the detection of ultrasonic impulses caused by changes within the structure of the material (cracks, for example). Comparing with vibration methods could detect cracks before a catastrophic failure (Christian Scheer, 2007).

Many processing techniques have been developed, the same as it exist studies about the proper location of the sensors. Previous studies proved that techniques such as frequency power spectra analysis, wave stream features correlation and entropy, results to be efficient monitoring crack propagation in gears isolated from other sources (Davide Crivelli, 2018).

Nevertheless, no device for monitoring AE on gears was found in the market (RM for devices on the market equal to 0).

Table 4 shows the results explained at this point.

Table 4. Acoustic emissions analysis summary

		RM
Failure mechanisms	Monitor micropitting	3
	Monitor pitting	9
	Monitor spalling	9
	Monitor root tooth breakage	3
	Monitor TFF and TIFF	3
Level of modification needed		9
Interferences filtering		3
Availability of devices on the market		0

The difficulty of the implementation according to Table 2 ranks in 3, since it is more complicated to install than a vibration measure system. It requires the installation of more sensors and/or the isolation of noisy devices near the rig.

4.3.3 On-line particles analysis

When the test starts the amount of metal particles in the lubricant system is minimum. As the test is running, the gears rotating and the contact surfaces of the teeth start deteriorating, more and more small particles of metal fall from the teeth and enter in the lubricant oil system. More deterioration is equal to more particles in the lubricant system.

The same happen in real gearboxes for example, in cars. It is common to incorporate a magnet in the bottom cup of the gearbox to capture the particles and avoid then to cause more damages crashing with the gears or other components. The number of metal particles in these cups is a visual and fast measure used by mechanics to rapidly examine the inner state of the gears. This process is visual and qualitative, nevertheless, a more efficient and exact method has been developed following the same principle and using modern data acquisition methods.

Bending fatigue mechanisms does not involve the fall-off of material, meaning that cannot be monitored by this method, also suggesting a RM value equal to 0 in the monitoring of bending fatigue mechanisms. Although micropitting could be detected but the method works better with bigger particles, the reason why RM is equal to 1.

It is possible to buy a device that measures particles in quantity and size—obtaining very good results in the monitoring of pitting and reducing the duration of the test and the human intervention drastically. The installation requires to connect the device in series with the lubrication system. Size there are devices available on the market, RM value is equal to 9.

One problem with this methodology is that it is not possible to filter particles from other sources. Other components also deteriorate during the test and add metal particles to the lubrication system. The only solution is to estimate the degradation speed of other components. RM value for the filter of interferences is 1.

This method proved to be useful in surface damage detection, reducing time intervals for visual inspection since the progression of macropitting failure is well detected by the number of metallic particles in oil (J. Kattelus, 2017). The RM value for pitting and spalling is 9 for these reasons. Table 5 gives a summary of the on-line particle methods based on the previous text.

Table 5 is a summary of the previous text showing the RM value of the different categories.

Table 5. On-line particles analysis summary

<table>
<tr><td colspan="2"></td><td>RM</td></tr>
<tr><td rowspan="5">Failure mechanisms</td><td>Monitor micropitting</td><td>1</td></tr>
<tr><td>Monitor pitting</td><td>9</td></tr>
<tr><td>Monitor spalling</td><td>9</td></tr>
<tr><td>Monitor root tooth breakage</td><td>0</td></tr>
<tr><td>Monitor TFF and TIFF</td><td>0</td></tr>
<tr><td colspan="2">Level of modification needed</td><td>9</td></tr>
<tr><td colspan="2">Interferences filtering</td><td>1</td></tr>
<tr><td colspan="2">Availability of devices on the market</td><td>9</td></tr>
</table>

The difficulty of the implementation according to Table 2 ranks in 1, since it only requires small modifications in the rig.

4.3.4 Visual recognition

The pit holes that appear on the tooth faces during the contact degradation process are the most apparent indicator of failure. Observe the tooth faces status is a common practice to determine the current status of gears.

It is important to clarify that the ISO 6336 that, among others, regulate gear test for pitting, requests visual assessment of the area and measure the percentage occupied by pitting craters, meaning all other detection methods are complementary.

Different approaches could be applied to exanimate the area: manually, semi-automatically and automatically visually.

Manually visually, evaluation of the surface is the method described in the point *2.6 Current durability test*. Since the surface is not visually accessible, the gearbox needs to be opened, checked, and started again in between certain intervals of time. The process is time-consuming, required a lot of human intervention and it is not easy to determine the exact moment of failure.

Semi-automatically, means that the rig is stopped, the teeth are cleaned, and fast pictures of the surfaces are taken with a camera. The method proved to be not time-consuming, since the acquisition of 16 teeth takes 5 minutes. After, the acquisition, the test can keep running, and images are processed in the meantime (image processing take 2 minutes for a picture of 6 megapixel) (Dynybyl, 2008). This methodology is not available on the market and reduce the time invested in each measure, but still required a lot of human intervention and results are not improved.

Other studies about detecting defects in gears are available. A similar work using machine learning (ML) and image recognition methods exists. It consists of the identification of manufacturing defects and quality inspection performance by using convolutional neural networks (CNN) (Liya

Yu, 2019). In spite the focus is different, since there are no many studies about it, it constitutes a good starting point.

The last approach, automatically, has never been attended. In spite of ML and CNN are used in other detecting methods, for making better models and anticipate failure in a better way, use it for visually recognize defects in the meantime the machine is running, it presents many problems for its development.

The main problem is the lubricant. Since half of the box is full of lubricant and the gears are rotating, the lubricant is scattered all around the volume, causing distortion in the image and adding interferences. Figure 20 shows the oil distribution inside a gearbox system when gears are running of two different lubricants. A good lubricant covers the gears as much as possible, creating interferences during all the operation time, the reason why deal with interferences in this methodology is a difficult task, and the RM value is 0.

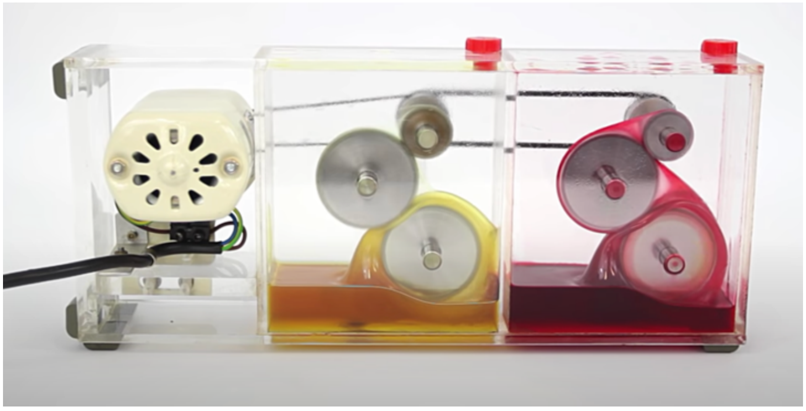


Figure 20. Lubricant distribution in a gearbox (Lubricants Omega, 2014)

Other problems include the integration of a high-speed camera (since rotation speed is too fast), the huge amount of light are necessary, a method that reduces or deal with the distortion caused by the rotational movement on the pictures and a good study that place all the elements in the correct position, since the space is small and the angles limited. The level of modification needed is high, and there is no device on the market that could be used, RM values are 0.

The last described method could detect all kinds of surface damages (RM equal to 9) and possibly superficial cracks too (RM equal to 1). Also, the ability to continuously monitor the changes in the tooth will increase the understanding of the fatigue mechanisms exponentially.

Table 6 summarize RM for a new automatic visual recognition method since a manual method is already in use and a semi-automatic method is an improvements to the measure method and not directly a detection methods, since it required to stop the test and open the gearbox for cleaning the surface and performed.

Table 6. Automatic visual recognition summary

		RM
Failure mechanisms	Monitor micropitting	9
	Monitor pitting	9
	Monitor spalling	9
	Monitor root tooth breakage	1
	Monitor TFF and TIFF	0
Level of modification needed		0
Interferences filtering		0
Availability of devices on the market		0

The difficulty of the implementation according to Table 2 ranks in 10, since everything in this method needs to be developed.

4.3.5 Electrical current analysis and temperature analysis

Electrical current and temperature are already being measured by the FZG rig but with different proposes. These two are needed to keep the test running under controlled conditions.

Electrical current is the one supplied to the engine to keep the rig running at the testing speed and overcome the losses and is directly related to the torque. On the other hand, temperature is related to the inner energy of the system and is proportional to efficiency loses that are transformed into heat. More loses is more heat, and heat increases the temperature of all the system.

Clearly, teeth surface degradation decrease efficiency which means that the motor has to supply more torque for moving the system which requires more electrical current and since losses are increased, and losses, at the end are transformed into heat, the temperature of the system increases too. In spite of this variable actually change during the lifetime of the gear, they may not result as good indicators for early detection in the FZG rig or in real gearboxes.

Analyze electrical current by applying discrete Meyer wavelet on 13 levels provides similar results to vibrations in large pits (Pavle Boshkoski, 2008). The RM value for pitting and spalling monitoring will be 3 and 9, respectively for this reason.

Temperature increases in the gearbox because of many reasons, not only because of surface degradation, making it difficult to predict where losses originate. Measure temperature in the gear flanks is not an easy task. It exists a device that can be incorporated into the FZG rig that replaces the axis where the gear is located.

This device is shown in Figure 21 and incorporates a sensor inside that make it possible to measure the temperature of the gear in the center of the axis but not on the teeth, reason why RM value for temperature devices on the market for early detect fatigue is 0. On the other hand, many devices able to measure electrical current are available on the market (RM equal 9).

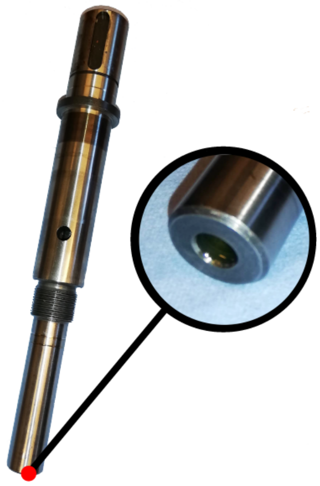


Figure 21. Axis device for measure gear temperature

No papers or methodologies which aim is to detect fatigue failure on gears by using temperature changes were found. Temperature is measured but with control purpose meaning to hold a certain temperature in the gearbox. Table 7 and 8 shows the summarize of the characteristics disused in this text of the electrical current method and temperature indicator, respectively.

Table 7. Electrical current analysis summary

		RM
Failure mechanisms	Monitor micropitting	0
	Monitor pitting	3
	Monitor spalling	9
	Monitor root tooth breakage	0
	Monitor TFF and TIFF	0
Level of modification needed		9
Interferences filtering		0
Availability of devices on the market		9

Table 8. Temperature analysis summary

	RM

Failure mechanisms	Monitor micropitting	0
	Monitor pitting	1
	Monitor spalling	1
	Monitor root tooth breakage	0
	Monitor TFF and TIFF	0
Level of modification needed		0
Interferences filtering		0
Availability of devices on the market		0

The difficulty of implementation of an electrical current measuring system is low, resulting in a value of 1 since only small modifications are required. On the other hand, a temperature measuring method needs many developments before being ready, resulting in a difficulty of 10.

4.4 QFD results: early fatigue detection in FZG rig

QFD methodology is the key tool for the decisions making process in this project. HOQ matrixes are printed in *APPEDIX D*.

By analyzing the rig and interviewing people working with the FZG machine the main objectives were determined. The main focus of improvements or desirable characteristic in the FZG rig for more easily detect fatigue on gears are:

- Reduce durability test duration (30,8%)
- Improve results (23,1%)
- Improve usability (make measurements easier) (30,8%)
- Scalability to industry (15,4%)

The durability test is a time-consuming task, the reason why it is interesting to reduce its total duration, the same as obtain as much information as possible from each test. It is also laborious and required many human interventions, so it is desirable to make its usage simpler. Even if knowledge obtained from the test is applicable to the industry it would be nice if the chosen technology could also be applied in industries.

It was also determined that *Reduce durability test duration* and *Improve usability* is double more important than the *Scalability*, the same as *Improve results* are 50% more important than the same objective. Resulting in the weights shows above.

4.4.1 First level: Objectives vs. Strategies

The first HOQ matrix relates Objectives mention above and Strategies. The full matrix is showed in Figure 27 located on the *APPENDIX D*.

To reduce the test duration, the strategies are *"minimize the number of visual assessments"* and *"minimize visual assessment time"*. Open the gearbox only when is necessary is strongly related to minimize de durability of the test and weakly related to the scalability and usability. Minimize the time that makes the measurements take is weakly related to reducing the test duration, size the influence on the total duration is lower, but improving the measurement process is strongly related to the improvement of the usability.

Improve results means to obtain more information from the durability test. By monitoring surface degradation and cracks growth, a better understanding of this process is possible to be archived. *"Monitor contact fatigue"* is strongly related to improving test results, while *"monitor bending fatigue"* is moderately related because during interviews, it was determined that gears mostly fail because of surface degradation. Monitor contact fatigue is also strongly related to minimizing the durability test time and weakly related to improving usability since with the monitoring of this mechanisms, it is possible to determine when measurements need to be done reducing human intervention.

Finally, it is desirable that investigation method could be applied in industry, reason why the *"level of modification needed on the rig"* is analyzed. If the intervention on the machine is low, there are more chances that the technology could be applied on machines on the industry. Reason why scalability and level of modification are strongly related.

Relative Weight	Weight / Importance	Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	Minimize the number of visual assessments	Monitor contact fatigue	Monitor bending fatigue	Level of modification of the rig	Minimize visual assessment time
30,8	2,0	Minimize durability test time	Θ	Θ			▲
23,1	1,5	Improve test results		Θ	O		
30,8	2,0	Improve usability (make meassurments easier)	▲	▲	▲		Θ
15,4	1,0	Scalable to the industry	▲			Θ	

Figure 22. Inputs in the first level HOQ

Results of the first HOQ are summarized in the following list:

- Minimize the number of visual assessments (23,3%)
- Minimize visual assessments time (22,2%)
- Monitor contact fatigue (37,5%)
- Monitor bending fatigue (7,2%)
- Level of modification needed (10%)

"Monitor contact fatigue" has the highest importance meaning is the most important strategy to be considered.

4.4.2 Second level: Strategies vs. Characteristics

In the second step more specific solution were consider for each strategy. The matrix is showed on Figure 28 located on the *APPENDIX D*.

For monitoring contact fatigue, the three main surface degradation mechanisms (micropitting, pitting and spalling) were considered. Same for monitor bending fatigue (TIFF and/or TFF and root tooth breakage).

The availability of signal filter methods is crucial (strongly related) for reducing the level of modification needed on the rig. Also, find a finish product in the market that could be install fast and with no previous work is strongly related to the level of modification needed.

The possibility of improving the visual assessment method (changing the stylus device) was considered to minimize the time that a person invests in making the measure or make simpler.

Relative Weight	Weight / Importance	Quality Characteristics (a.k.a. "Hows") / Demanded Quality (a.k.a. "Whats")	Monitor micropitting	Monitor pitting	Monitor spalling	Monitor root tooth cracks	Monitor TIFF and/or TFF	Interferences filtering	Availability of devices on the market	Change visual assessment method
23,3	323,1	Minimize the number of visual assessments	Θ	Θ	Θ					
37,2	515,4	Monitor contact fatigue	Θ	Θ	Θ			O		
7,2	100,0	Monitor bending fatigue				Θ	Θ	O		
10,0	138,5	Level of modification of the rig						Θ	Θ	
22,2	307,7	Minimize visual assessment time							Θ	Θ

Figure 23. Inputs in the second level HOQ

After the calculations on the QFD were made, the following results were obtained:

- Monitor micropitting (22%)
- Monitor pitting (22%)
- Monitor spalling (22%)
- Monitor root tooth cracks (2,6%)
- Monitor TIFF and/or TFF (2,6%)
- Interferences filtering (9%)
- Availability of devices in the market (11,7%)
- Change visual assessment method (8,1%)

According to the results, it is highly recommended to use a method that can detect different forms of surface deterioration. It is also recommended to acquire a device already developed, the same as technologies with filter methods available.

4.4.3 Third level: Characteristics vs. Technological solutions

The previous characteristics needs to be materialized in a formal decision. In order to do that, the previous characteristics were related to technological solutions in the third matrix. The matrix is showed on Figure 29 located on the *APPENDIX D*.

Each methodology included in the matrix has been analyzed in the point *4.3 Early failure detection methodologies analysis.* Two more options were also considered, a *"combination of vibrations analysis and AE analysis"* and find a *"new stylus measurement method"*. The first added option was included because on the interviews it was clear that is the method chosen by industry and the second one because could be interesting to see the effectivity of update the current method with a newer tool.

The combination of acoustic emissions and vibrations has all the advantages of the independent methods. Still, a difficulty of 4 since methods needs to be integrated, and the availability of the device on the market same as the availability is only partial—reasons why RM value is 1.

In the case of the new stylus, it is evident that it is strongly related to change visual assessment method, and many options are available on the market.

Relative Weight	Weight / Importance	Demanded Quality (a.k.a. "Whats") \ Quality Characteristics (a.k.a. "Hows")	Analysing vibrations	Analysing acoustic emissions	Analysing on-line particles	Analysing temperature	Analysing electrical current	Automatically visually measuing the area	Combining vibrations and acoustic emissions	New stylus measure method
22,0	545,0	Monitor micropitting	▲	O	▲			Θ	O	
22,0	545,0	Monitor pitting	Θ	Θ	Θ	▲	O	Θ	Θ	
22,0	545,0	Monitor spalling	Θ	Θ	Θ	▲	Θ	Θ	Θ	
2,6	65,0	Monitor root tooth cracks	▲	O				▲	O	
2,6	65,0	Monitor TIFF and/or TFF		O					O	
9,0	223,3	Interferences filtering	Θ	O	▲				Θ	
11,7	290,0	Availability of devices on the market	O		Θ		Θ		▲	Θ
8,1	200,0	Change visual assessment method								Θ

Figure 24. Inputs in the third level HOQ

Table 9 shows the considered technological solutions, the resulted importance and the difficulty.

Table 9. Results from QFD

	Importance (%)	Difficulty
Measuring vibrations	16,1	2
Measuring acoustic emissions	15,1	3
Measuring on-line particles	16,0	1
Measuring temperature	1,3	10
Measuring electrical current	11,1	1
Automatically visually measuring the area	17,9	10
Combining vibrations and acoustic emissions	17,1	4
New stylus measure method	5,3	3

Table 9 shows the four most important technological solutions have a similar impact on the objectives, being the development of a new visual method the highest and the analysis of on-line particles the lowest, with a difference lower than 3%. Results are more easily visualized in a graphic.

Figure 25 is obtained by plotting the previous results summarized in Table 9. The red line represents the difficulty of implementation and the blue line the importance of each technology according to the initial objectives. Technologies in the graphic are ordered by Importance, form the lowest to the highest.

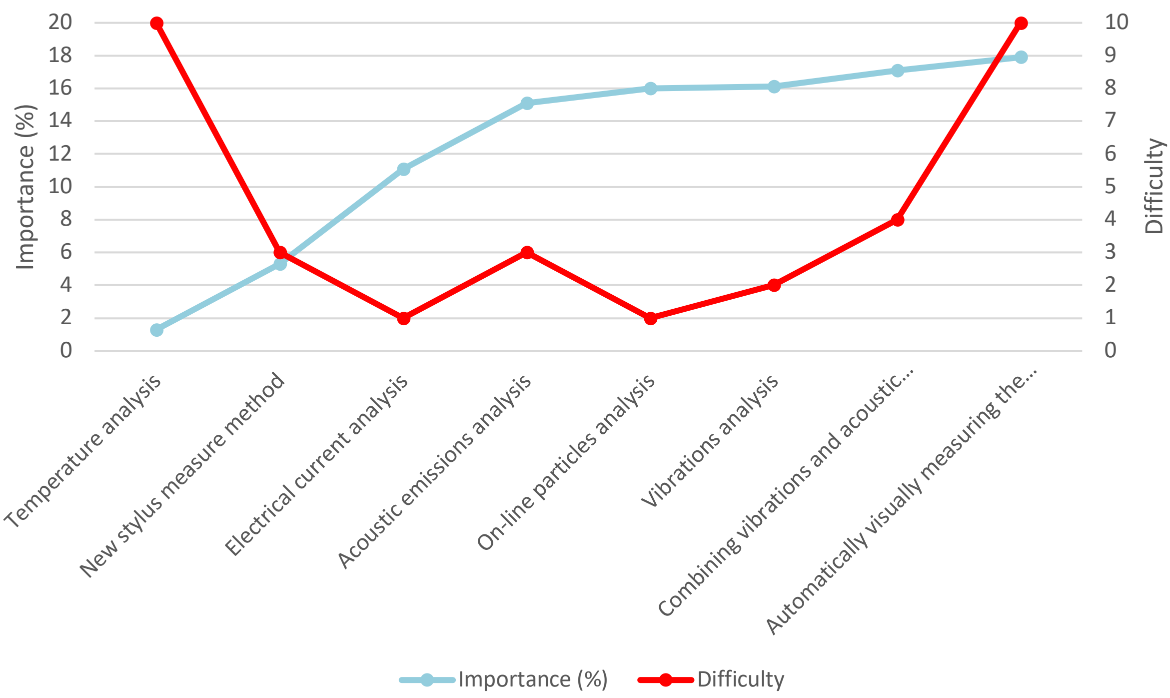


Figure 25. Most important results from QFD

The first three points show a tendency to decrease in difficult and increase in importance. The fourth increases considerably in importance with an increase in difficulty too. From the fifth to the last, a clear trend is observed, by increasing difficulty, increases also the resulted importance.

The first four technologies in the graph are *"temperature analysis"*, *"new stylus measure method"*, *"electrical current analysis"* and *"acoustic emissions analysis"*. None of these technologies represents a good solution by itself since the technological solution, *"on-line particles analysis"*, accomplish higher results with a lower difficulty.

As was mentioned before, in the best four technologies in the rank, there is a clear trend between difficulty and importance. More difficulty in the implementation also leads to a better fulfillment of the objectives.

On-line particles and vibrations have similar values of importance and difficulty. Depending of the preferences of the client the best solution may be one of the other. Vibrations analysis method is widely investigated, and many method and models are already developed, while on-line particle analysis is available on the market and easy to install.

The development of a new automatically visually measuring method for monitor surface degradation resulted in being the methodology that better fulfills the objectives since it can correctly monitor the transformation reducing the duration of the test, the human intervention and providing better results. On the other hand, the method has never been attended, there is no experience with it, the machine has to be drastically modified and the issue of visual interferences caused by the lubricant has not been solved yet—reasons why the difficulty of implementation has the highest possible value. A user looking to develop the best possible technique for early detect surface damage and get the best possible understanding of these mechanisms should choose this path.

Finally, combining vibrations and acoustic emissions it is the best solution considering the difficulty of implementation and the results of the QFD. This is concluded because of the difficulty of implementation is half the value on a new visual methodology and the importance is almost the same.

4.5 Summary column results

Results from the Summary column are presented in Table 10, the highest values of each level are colored.

Table 10. Summary column table

Matrix	Characteristic	Summary
Objectives	Minimize durability test time	1,621
	Improve test results	1,925
	Improve usability (make measurements easier)	2,567
	Scalable to the industry	1,540
Strategies	Minimize the number of visual assessments	0,863
	Minimize visual assessments time	1,233
	Monitor contact fatigue	1,240
	Monitor bending fatigue	0,343
	Level of modification needed	0,556
Characteristics	Monitor micropitting	1,294
	Monitor pitting	0,449
	Monitor spalling	0,400
	Monitor root tooth cracks	0,325
	Monitor TIFF and/or TFF	0,433
	Signal filtering	0,409
	Availability of devices on the market	0,532

	Change visual assessment method	0,900

This table shows that micropitting is an important failure mechanism that will require more investigation, size the summary value is high.

Also, many characteristics directly related to improve the usability have high values. Meaning this aspect was probably underestimated during the project.

5 DISCUSSION AND CONCLUSIONS

A discussion of the results and the conclusions that the authors have drawn during the Master of Science thesis are presented in this chapter. The conclusions are based from the analysis with the intention to answer the formulation of questions that is presented in Chapter 1 INTRODUCTION.

5.1 Discussion

At the beginning of this thesis, five research questions were formulated. The research questions were:

1. Which are the different failure fatigue modes in gears?
2. Which are the different fatigue failure mechanisms on gears?
3. What are the methodologies of early fatigue failure detection on gears?
4. How are fatigue failures detected in the industry today?
5. Which would be the best applicable methodology for early failure detection in the FZG-rig?

Two main fatigue failure modes have been identified according to the cause of initiation: contact fatigue and bending fatigue. Different mechanisms leading to contact fatigue, being initial pitting, micropitting, pitting, and spalling, same as in bending fatigue, being root tooth breakage, TFF, and TIFF. Figures 18 and 19 are a good summary of these phenomena, organizing fatigue modes and mechanisms and comparing the different phenomena in size. It was also concluded that pitting is the main reason for failure in gears that works in the correct operating conditions.

Read the information progressively was a success, making possible to address tons of useful information in a relatively short time.

The understanding of the degradation process helps in the identification of the indicators for monitoring its status. The fatigue process is continuous, and it is possible to monitor. During this process, the expected behaviour of the FZG rig changes, allowing engineers to measure and analyse these changes to determine the gear status. The main indicators of this process are:

- Vibration analysis
- Acoustic emission analysis
- Visual deterioration analysis
- Particles in the lubrication system analysis
- Temperature analysis
- Electrical current analysis

However, analyze temperature is not a good solution, since it is difficult to implement, and the improvement of the results is poor.

Many methods of all analysed indicators are available. During the realization of the thesis there was no opportunity for testing them. A precise comparation of the different methods would be desirable in the future, requiring a data set of the different indicators that also requires the addition of sensors in the FZG rig. The following step in this investigation would definitely be the design of data acquisition methods, in order to obtain data for further investigations.

In industry, the main analysed indicators are vibrations and acoustic emissions. Comparing with results obtained in the QFD makes sense. It is the best solution regarding fulfilment of objectives and difficulty of implementation, but also the analysis of the information provided by this system allow a wide monitoring of different failure modes.

Even when the literature about the topic is rich, the interviews were the best source of information, even when just a few were done. Performing more interviews would be a good strategy to increase the knowledge in this field, since experience is the best teacher.

QFD proves to be an appropriate technique to decide between different technologies. The summary column does not contribute with as much information as was expected, but analyzing its results, it was noticed that most of the characteristics related to improve usability, such as minimize the visual assessment time has a high value, meaning that the strategy may be underestimated and not enough effort was invested on it during the application of the QFD. Also, the value for micropitting detect techniques is high, meaning that more techniques for detecting this phenomenon may need more attention in the future.

Final results from QFD, show that the solution that better fulfil the objectives is the development of a new automatic visual method. However, the level of difficulty of this task is also high, the reason why it is not a good solution for the FZG rig on KTH.

The Machine Design department should instead implement a combination of vibrations analysis and acoustic emissions analysis. This methodology would give the department-wide monitoring options for all failure mechanisms with a reasonable level of difficulty.

5.2 Conclusions

The following conclusions can be made based on this study:

1. According to the interviews performed, gears working in optimal conditions mostly fails because of surface deterioration (contact fatigue).

2. The most promising monitoring methodologies analysed in this project for early detect fatigue failure on gears are:
    - Vibrations analysis
    - Acoustic emissions analysis
    - On-line particles analysis
    - Visual inspections
    - Electrical current analysis

3. According to the QFD results in this study, a new methodology using visual recognition would be the solution that would better fulfil the objectives of the FZG rig.

4. The suggested and most promising methodology for more easily detect fatigue failure on the KTH FZG rig is a combination of vibrations analysis and acoustic emissions analysis.

6 RECOMMENDATIONS AND FUTURE WORK

In this chapter, recommendations on more detailed solutions and/or future work in this field are presented.

6.1 Recommendations

The principal and more important recommendation is to understand the huge lack of sensors that the FZG rig has. Nowadays, none cost or technological barriers are impediments to accurately measure the behavior of the components of the machine. A rig test machine used for investigation should count on these acquisition methods.

Also, electrical current may not be a good solution for its own because the sensibility to small pits is low. Still, it is a straightforward implementable system that can reduce the durability test time with low efforts.

The construction of a well-organized data base where engineers could upload data from test will set the bases for considerable improvements in the field. Since there are many FZG rig installed in the world, an open data base will encourage engineer to work in this field.

In spite is not the focus of this project, during the first steps in this long project, some data form the previous test made on the FZG rig were examined. Some of the data came from efficiency tests. There are enough reasons to think that a good model using temperature (in particular the signal TEMP_SGB), speed and load, could be performed in other to better anticipate efficiency on gears. The use of this variable in model realization is highly recommended.

6.2 Future work

To better detect fatigue on gears a better understanding of the process is necessary. The total understands of surface degradation required of methodologies that could detect the exact moment of failure. All indicators analyzed in this thesis are not capable of monitor surface degradation with that level of precision, but an automatic visual analyzed method. Future studies in the direction of better monitor surface fatigue are highly recommended. In particular, studies that help in the development of technology is based on visual recognition to measure the degradation more often with more precision constitutes an excellent opportunity.

The method previously described will increase the knowledge in the field. Still, it is not implementable in most of the industries and machines, because of many reasons, including size and price. Definitely, that knowledge needs to be applied in the realization of models that rely on more easily implantable methodologies. The modification of the FZG rig by adding a sensor is highly necessary. It will allow the construction of data sets with all the required information for testing and developing new models for anticipate or early detection failure on gears.

The mentioned data sets are key points in the creation of new models. In particular, ML expanded the possibilities in the world of model realization. These techniques are being applied in many fields in the latest years, leading to improvements in many sectors. There are many reasons to think that the application of these techniques in the field of early failure detection on gears it will be very beneficial. Future studies in the creation of new models by using ML techniques are recommended.

Finally, mention that new models will be as good as data will be, the same as development speed would be directly related to the organization of the data. Any model realization technique, in particular ML techniques, requires good data, with a high level of organization and as standardized as possible.

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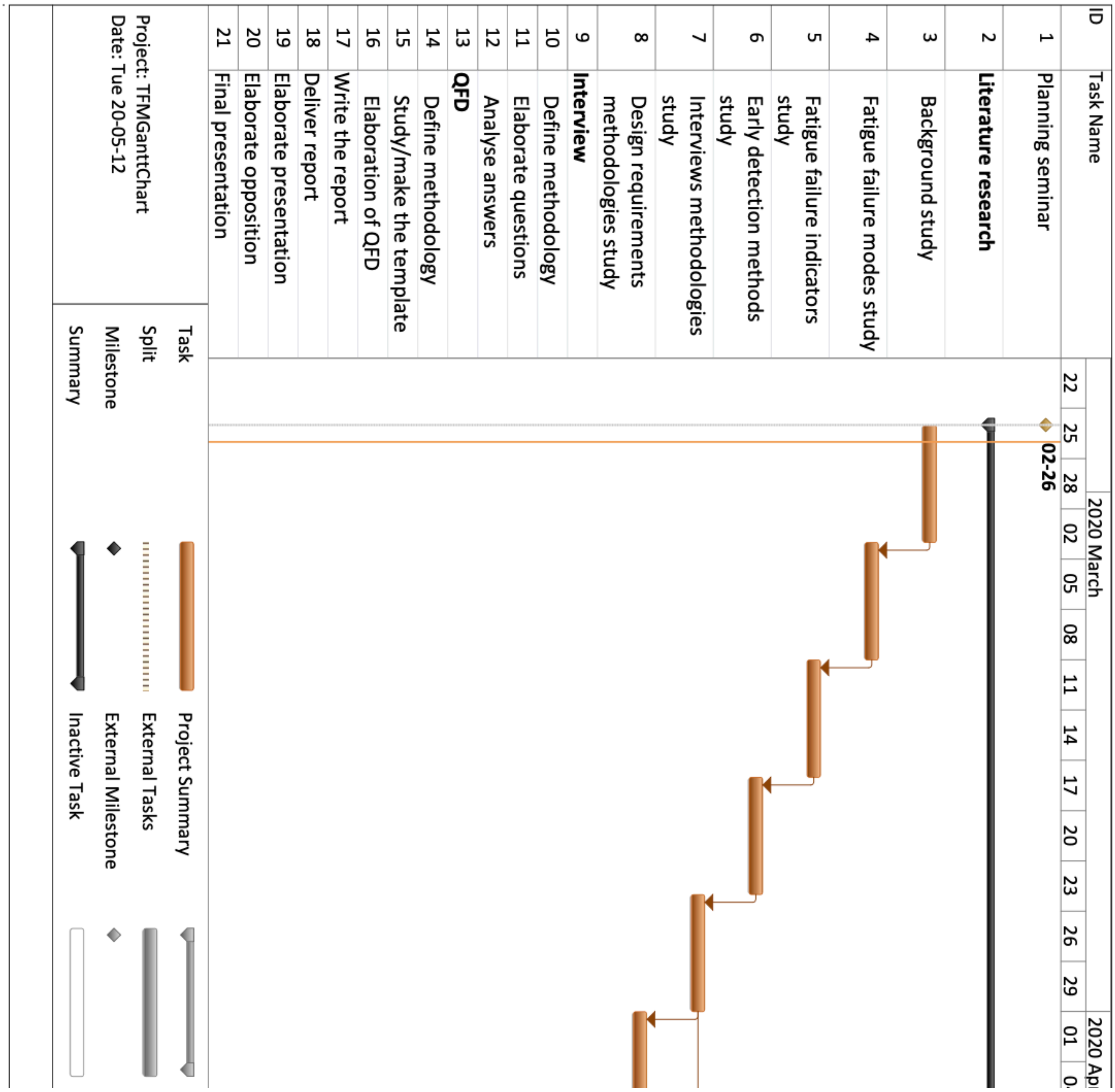
8 APPENDIX A: TIME PLANNIFICATION

Planification and time managing is important in every project and is an invaluable ability for every engineer and professional of every field. The APPENDIX A shows the necessary task to do in to accomplish this project, as well as the estimate time, the milestones and the available time.



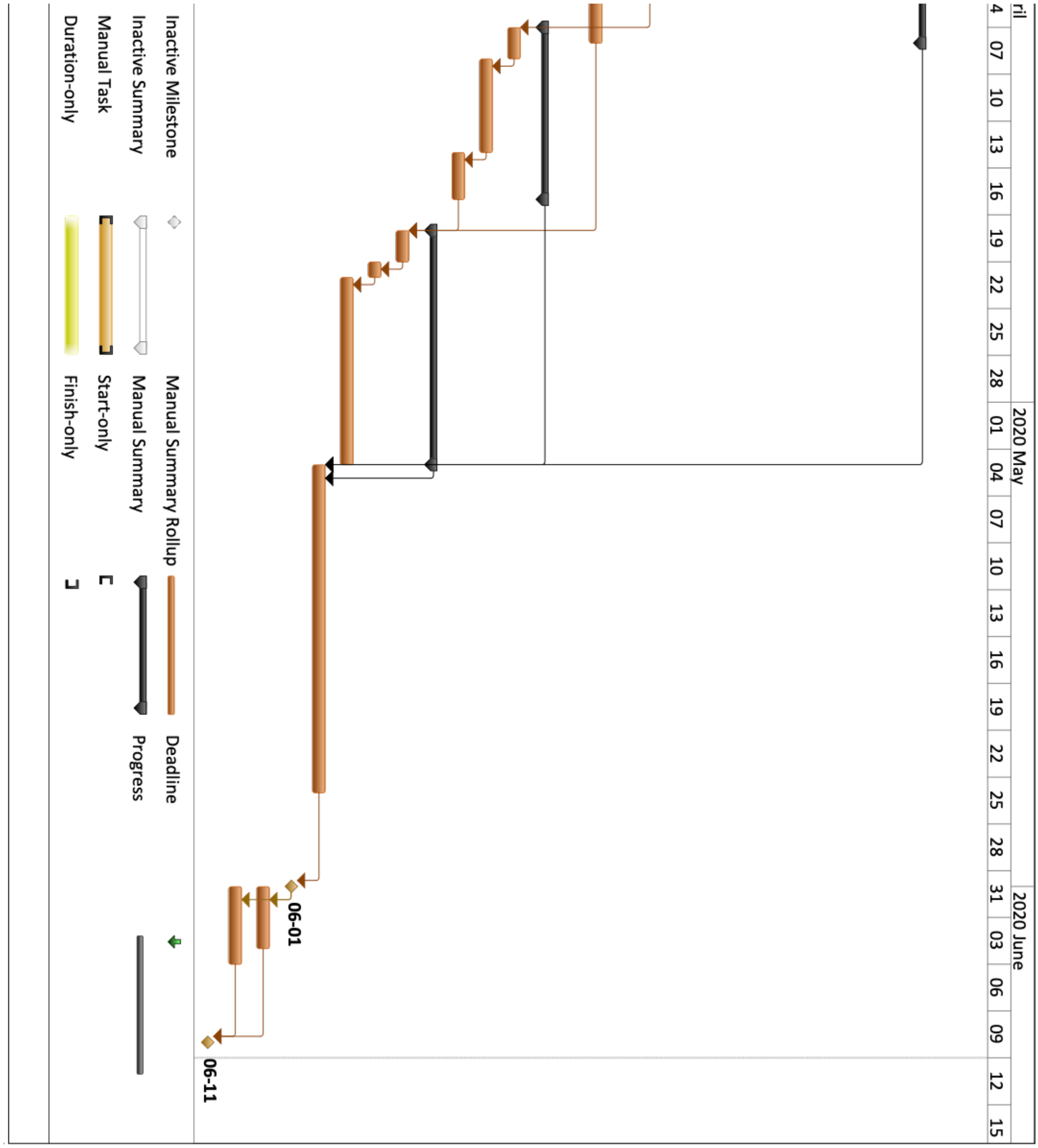


Figure 26. Gantt Chart

9 APPENDIX B: RISK ANALYSIS

In every project, it is a chance that problems appear, and things just do not work. It is important to anticipate these problems and plan a response to be prepared if these events happened to occur.

The following table shows the identified risks, as well as the like hood and the planned action. Both, like hood and consequence are on a scale from 1 to 10, being 1 very low probability of occurrence and/or very low impact in the project and 10 very high chance of occurrence and/or very high impact in the project.

Table 11. Risk Analysis

Risk	Like hood	Consequence	Planned Action
Lose all information stored on computer	1	9	Reduce the risk by using cloud system. Download Google Drive and Microsoft Outlook.
More difficulty than expected in find and sort information about the topic	5	3	Take a course in the liberty about how to do this properly and more efficiently. Use a progressive approach.
The access to some papers is restricted	5	4	Ask the department and companies if they do have the documents. Do not take them into consideration.
Availability of relevant people for interview is low	8	4	Make interviews on available times and analyze it when is schedule.
Not finish on time (before mid-June)	3	5	Ask for an extension on Erasmus program and presented as soon as possible after summer.
SARS-CoV-2 situation gets worse	8	5	Work from home. Preform interview and meetings by using remote communication tools.

10 APPENDIX C: INTERVIEW QUESTIONS AND ANSWERS

In the APPENDIX C, relevant answers of people related to the FZG rig and early fatigue detection are presented. Answer that contain personal information (presentation or first part of the interview) were not included in order to keep the privacy of the interviewed people. Also, not relevant answers are not included. The analysis and method are presented in the point 3 METHOD and results in the point 4 RESULTS.

Current situation

- **What machine do you use for testing gears?**
  1. We mainly test whole actual truck gearboxes. They are driven by big electric motors which can apply a torque of ~30kNm. But then Scania also has the same FZG test rig which you have at KTH.
  2. FZG gear test rig.
- **Between all indicators that the machine measures, what are the indicators that you actually use for detecting surface damage on gears?**
  1. If the gearbox is assembled correctly and the parts are of good quality the most reliable source of information is sound and vibration.
  2. My main focus was on helping to develop a High-Performance Planetary Gear Test Bench for Aviation. However, I also worked with the FZG gear test rig for testing and evaluating different kinds of oil. Surface damage on gears were mainly investigated by my colleagues using visual indicators and scanning electronic microscopes.
- **Could you describe the method used in the durability gear test?**
  1. One gear shift is tested at the time at a given load. After a certain number of rotations, the gears are unloaded for a short while and then the load is applied again. This repeats until hopefully the gears breaks.
- **What sensors are used?**
  1. I don't have any information about the sound and vibration sensor unfortunately. For temperature measurements PT100 sensors are often used.
  2. We have installed temperature sensors in the gears.
- **Do you have any special reason for <u>not</u> use any indicator?**
  1. In testing you should definitely use sensors. Maybe they are not as important as you decrease the torque you apply and the input speed. Trucks on the road loaded with sensors and systems telling you the conditions.
  2. No, according to my experience.
- **According to your experience, what is the main fail mode in gears?**
  1. Surface induced damages, which can depend on many things. As gear steel cleanliness increases, the manufacturing procedure is refined, tooth interior fracture fatigue can also occur as the demands of gearboxes to operate at a longer time is increased.
- **According to your experience, what is the main fail mode in gears? Do you know any method for detecting or monitoring tooth flake fracture (TFF) and/or tooth interior fatigue fracture (TIFF)?**
  1. Surface induced damages, which can depend on many things. As gear steel cleanliness increases, the manufacturing procedure is refined, tooth interior fracture fatigue can also occur as the demands of gearboxes to operate at a longer time is increased. There are probably several surveying methods on the market. I know one which Scania use. It is not entirely focused on TIFF. It measures sound/vibration and keeps track of it. It will be a history of vibration data where you can see trends.

- **Is it you company working on it?**
  1. Scania is not developing any equipment for detection, it is bought.

Past situation

- **Do you remember how surface damage detection was done in the past?**
  1. I don't know. I have to ask other people who have worked here longer than me, but I would guess it was also with sound/vibration.
- **What are the previous indicators used in the past?**
  1. An increased vibration levels.

Future situation and extra comments

- **Is your company currently trying to improve the system to detect surface damage?**
  1. Yes, to detect a damage as early as possible is desired.
- **Based on which indicators or method?**
  1. This is mainly done with sound/vibration.
- **Any other observation or comment regarding the topic?**
  1. ISO 6336 requests visual assessment of area percentage occupied by pitting craters. This is the ultimate way.

11 APPENDIX D: QFD ANALYSIS

In the APPENDIX D, the QFD are presented. Same as a table with the calculated Summary according to equation 1.

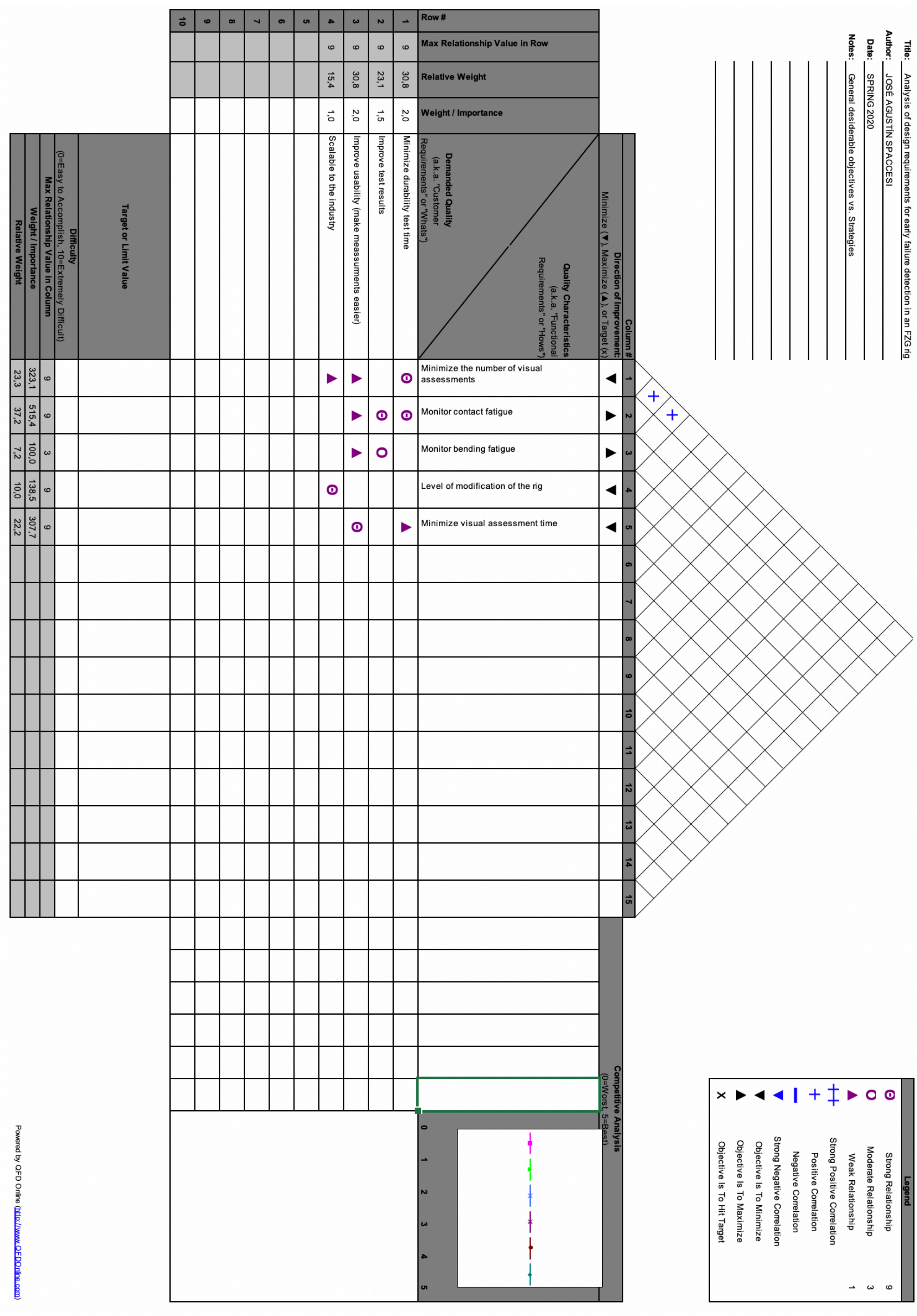


Figure 27. First HOQ: Objectives vs. Strategies

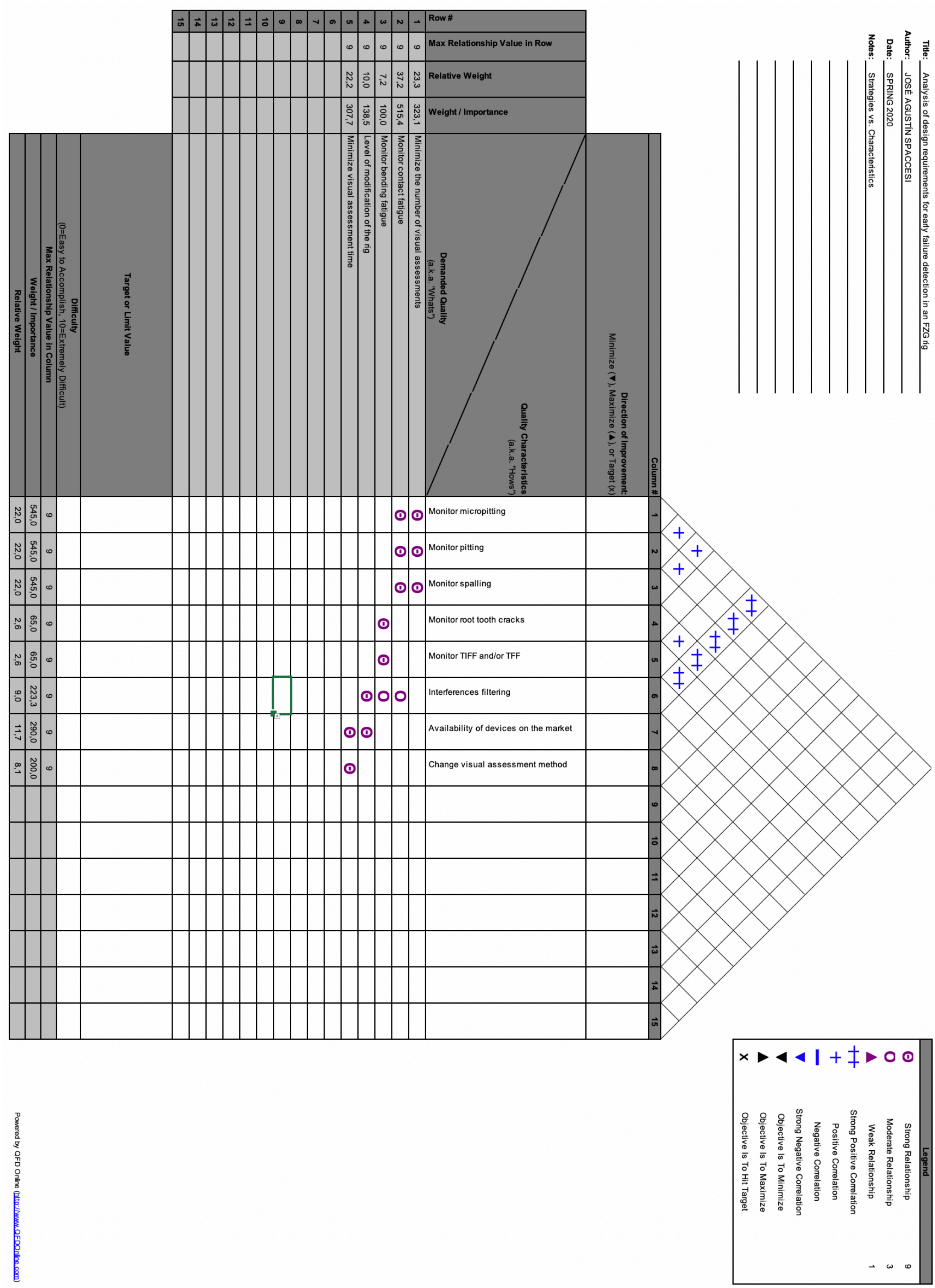


Figure 28. Second HOQ: Strategies vs. Characteristics

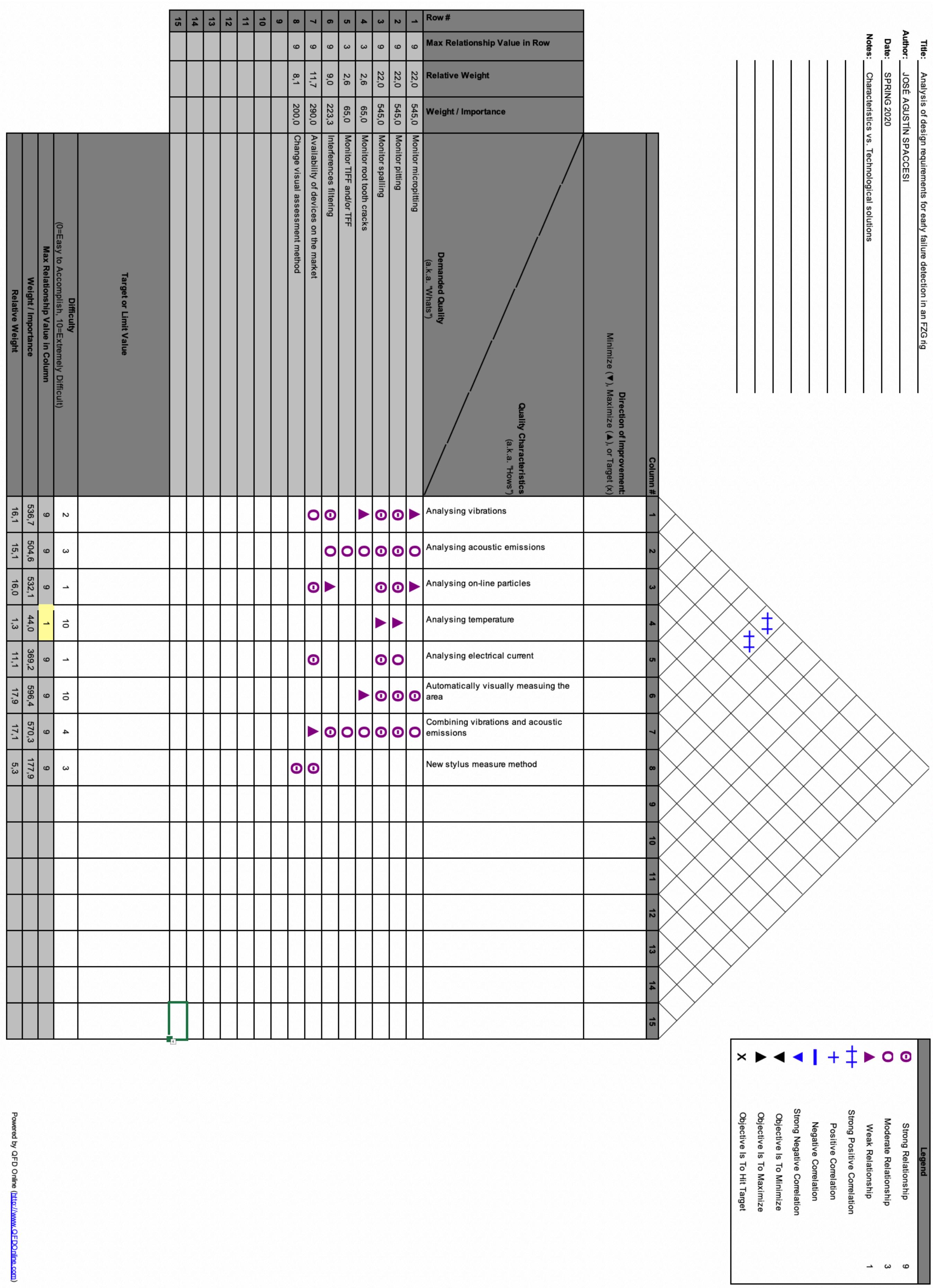


Figure 29. Third HOQ: Characteristics vs. Technological solutions

12 LIST OF FIGURES AND LIST OF TABLES

In this chapter a list of the figures and tables used in the report is located.

List of figures

List of tables