Robot Condition Monitoring and Production Simulation

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“An investment in knowledge pays the best interest”

Benjamin Franklin
Abstract

The automated industry is in a growing phase and the human tasks is increasingly replaced by robots and other automation solutions. The increasing industry entails that the automations must be reliable and condition monitoring plays an important role in achieving that ambition. By utilizing condition monitoring of a machine it is possible to detect a wear before it turns into a critical damage that could result in complete failure. A useful tool when monitoring the condition of a machine is by sampling and analyzing vibrations. Vibrations are generated by the moving parts of the machinery and high amplitude vibrations can often be seen as an indication of the developed faults. The frequency of these vibrations can be calculated and then detected in the sampled data.

Today there is no condition monitoring system that monitor industrial robots by analyzing vibrations. The problem with analyzing robots, is that they operate with a varying speed. Since the running conditions are changing rapidly all the time, this means that the vibration frequencies also changes constantly. This is due to the fact that the vibration frequencies are dependent and affected of the operation speed.

This research is a sequel and continuation of a research from previous year. The purpose of the research is to investigate the possibility to monitor the condition of a gearbox in a industrial robot, by utilizing vibration analysis. The robot that has been tested under tuff conditions in order to reach a failure, is an ABB IRB 6600. To sample data in a stationary way even tough the speed is changing during the sample time, the method order tracking has been utilized. This makes it possible to sample data with numbers of measurement per rotation instead of sampling according to time. This is processed by SKF:s condition monitoring system multilog IMx and the signal is then presented as a time waveform in the software @ptitude Observer. In Observer, it is also possible to show the signal in a spectrum by using Fast Fourier Transform. By utilizing MATLAB, the research has also resulted in a new analyzing method. This method is called Spectral Auto-Correlation. The methodology of this practice is to correlated the time waveform with itself in order to see which frequencies that are reappearing. The correlated result is then calculated with a Fast Fourier Transform to illustrate the signal in a spectrum for further analysis.

During the analysis of the parts in the gearbox, critical defects were found on both the cycloidal disks. The fault frequency for the defects were calculated and analyzed from the data. This resulted in trends where the amplitude from the fault frequency had more than doubled over the time the robot has been operating in the project.

This report also include a production simulation where a robot cell from SKF is simulated. The robot cell is simulated with and without a condition monitoring system. A comparison was then made to see what advantages there were with utilizing a condition monitoring system. The result of the simulation was an increased productivity with two to three percent.
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List of Abbreviations

TRB  Tapered Roller Bearing
ACBB Angular Contact Ball Bearing
CRB  Cylindrical Roller Bearing
FFT  Fast Fourier Transform
OT   Order Tracking
FTF  Fundamental Train Frequency
BSF  Ball Spin Frequency
BPFO Ball Pass Frequency of the Outer race
BPFI Ball Pass Frequency of the Inner race
Nb   Number of rolling elements
S    Speed
Bd   Ball diameter
Dp   Pitch Diameter [mm]
Dm   Outer raceway Diameter
dm   Inner raceway diameter
Dp*  Pitch Diameter (for tapered roller elements)
SK   Spectral Kurtosis
CCM  Current Condition Monitoring
SES  Simple Exponential Smoothing
RMS  Root Mean Square
AC   Auto Correlation
SAC  Spectral Auto-Correlation
CM   Condition Monitoring
FFT  Fast Fourier Transform
GMF  Gear Meshing Frequency
GNF  Gear Natural Frequency
MTBF Mean Time Between Failure
MTTR Mean Time To Repair
Chapter 1

Introduction

Maintenance is an essential procedure in order to maintain condition and quality of a product or a tool set. Maintenance procedures has undergone some evolutions throughout the years. The maintenance process has primarily been a reactionary procedure, whereby a component or machinery has been replaced when deteriorating. However, this methodology of responding to failures seemed inefficient and primitive, when it left the proprietor unaware of when the next incident might occur. By understanding the benefits of being able to foresee an eventual failure, the first evolution of machine preservation took place. By adapting statistical models such as the bathtub curve [1], many of the maintenance operations were done preemptively instead of reactionary, which changed the methodology and philosophy of the practice. This attitude of intervening before complete failure, led to more reliable and predictable machinery. However, utilizing a statistical method to predict eventual failures proved ineffective in some circumstances. For an example, machinery or components might fail before scheduled maintenance due to relying on “an educated guess”. Furthermore, components that were scheduled for replacement might have still been adequate operational, resulting in unnecessary waste. From this predicament, condition monitoring as we know it, was born.

By utilizing sensors and software, the proprietor was now able to monitor the condition of the machinery. Enabling the availability of scheduling maintenance reactively and assessing the underlying problem. This proceeding is already widely adopted in cyclostationary applications and is considered a common practice. However, further studies within the subject reveals a knowledge gap when adopting the methodology to a non-cyclostationary environment. Robotics, a highly advanced and expanding market, is just one example of non-cyclostationary operation that is in dire need of an advanced condition monitoring system. The aspirations of such implementations would be to reduce unnecessary production stops and pave the way for digitalization and industry 4.0. The pursuit of condition monitoring and machine preservation is to achieve 0% downtime in an operational production line, thus illustrating the importance of an integrated condition monitoring system. Therefore, SKF undertook a collaboration together with Luleå University of Technology to evaluate predictive maintenance and condition monitoring of industrial robotics, in this master thesis project called Robot Condition Monitoring and Production Simulation.
Chapter 2

Theory

2.1 State of the Art

This section will present the state of the art analytics in the field of condition monitoring and acknowledge previous work within the field.

2.1.1 Previous Work

During the preliminary investigation and literature study, the authors found insufficient information about non-stationary and Robot condition monitoring, resulting in a knowledge gap within the specific research field. That being said, a fair amount of relevant progress has been made within the field of cyclostationary condition monitoring that could be applicable for this kind of operations. With the prior knowledge in cyclostationary condition monitoring and the experience from the previous master thesis project in collaboration with SKF [2], has enabled the further studies within the field of non-stationary condition monitoring.

The challenge of this research is to apply the preceding findings from a cyclostationary environment to a setting that is suitable for a non-stationary operational industrial robot.

2.1.2 Condition monitoring

In today’s industrial environment, an unplanned production stop is highly expansive for the corporations. One of the main reasons for these interruptions are due to machine failures. To decrease the risk for severe machine failures, it is possible to integrate condition monitor (CM) into the process [3]. CM assess the condition of the machine and discover defects before complete failure. This is done by different analyze methods depending on what is suitable for the current situation. Vibration, temperature and lubrication is some parameters that could be analyzed and give information about the condition of the apparatus.

For rotating machines, the most common method is to analyze the vibration from the bearings. These vibrations can be measured during ongoing operations, resulting in no necessary downtime and increased effectiveness. Thus, allowing the continuing evaluation regarding the condition of the machinery, which ultimately enables the early detection of arising defects [3].

2.1.2.1 Time Waveform

The time waveform is a frequently used technique to analyze vibrations over time. It is a useful tool when it comes to condition monitoring and diagnosing wears. The vibration signal is plotted as an amplitude over a time scale, illustrated by figure 2.1.
Chapter 2. Theory

FIGURE 2.1: Time Waveform analysis

The sine wave illustrates what is happening in the element from one moment to another, due to continuous recording of the vibration pattern from the component. If there is any crack or other relevant damage, it will be seen as spikes in the sine wave, making it available for further analysis [4] [5].

From the time waveform, it is possible to break down the signal into specific amplitudes where the frequency is various. This is done by applying the Fast Fourier Transformation, see chapter 2.1.2.2 [6]. The time waveform can be used to indicate the true amplitude in situations where effects appear, such as assessing the severity of a rolling element defect. It is also a useful tool when analyzing vibrations and determine the condition in example gears [7].

2.1.2.2 Fast Fourier Transform

The Fast Fourier Transform (FFT) is a significant signal analysis method in condition monitoring. When sampling vibrations in the time waveform there can be a lot of different frequencies, both relevant and noise. The sum of these frequencies is the result of the measurement and what the time waveform will display. All the frequencies can be explained as different sine waves and can be seen in figure 2.2. The figure show that the curve in the time waveform consists of three sine waves. FFT is utilized to distinguish the different sine waves with their frequencies into individual spectral components with the amplitude of each sine wave, as can be seen as spikes in figure 2.2. So when applying FFT, the data is showed in frequency against amplitude, which facilitate the analysis of the signals when searching for different frequencies [8] [9].
2.1. State of the Art

2.1.2.3 Order tracking

Order tracking is a way to sample the vibrations when the rotational speed is changing over time [10]. When sampling at a constant frequency, which is measured in Hz (cycles per second), and as the speed is changing, the evaluation of the measurement will be difficult to analyze. This because, if the speed is increasing the frequency will sequentially also increase, which will lead to an unsynchronized sampling [11].

Order tracking is measuring in samples per rotation and is named as orders, which means that the orders are constant to the rotation. The first order for example means that there is one sample each rotation, the second two samples each rotation and so on. So, the speed can change over time and the result will still be functional to analyze [10]. To get a better understanding, an example illustrates this methodology in figure 2.3, where the measurement ranges from 30 Hz to 100 Hz with a time span of two seconds [11].

Figure 2.4 represent the same measurement with frequency from 30 Hz to 100 Hz, but after a FFT.
In figure 2.5 the FFT plot change from measuring in frequency to orders. Even if the frequency changes over time, the orders remain constant. The signal sampling at order one which means that there is one pulse each rotation [11].

2.1.2.4 Simple Exponential Smoothing

The idea with Simple Exponential Smoothing (SES) is to get a smoother curve. If a signal has a great diversification, it can be hard to detect the pattern. With SES the signal is affected of the previous data. If we have signal $T_n$, where $n$ is the amount of measures and $\alpha$ is a “smoothing constant” between 1 and 0. The SES will then be represented by equation (2.1) [12].

$$T_n = T_n(1 - \alpha) + T_{n-1}\alpha \tag{2.1}$$

$\alpha$ can be seen as how many percent of the new signal that will be affected and $T_n$ will advance exponential with the amount of measurements.

2.1.2.5 Root mean square

Root mean square (RMS) is used in this research to get an average value of a peak or a frequency range in the spectrum [13]. The formula can be seen in equation (2.2), where $a$ is the amplitude and $n$ is the amount of data.

$$RMS = \sqrt{\frac{1}{n} \sum_{i=1}^{n} a_i^2} \tag{2.2}$$
2.2 Hardware

2.2.1 The Robot

The robot used for this master thesis project was an ABB IRB6600, commonly used industrial robot and widely employed in the car manufacturing industry [14]. Versatility is one of its strong suits as it has a variety of applications, ranging from spot welding to machine tending operations [15]. Due to its popular utilization in a manufacturing and production setting, the model is a sufficient candidate for a non-stationary condition monitoring research project. An illustration of the robot can be seen in figure 2.6.

![Figure 2.6: ABB IRB6600 schematic [16]](image)

As previously mentioned, the IRB6600 is a versatile and flexible industrial robot, capable of handling loads up to 255 kg with a reach of 2.55 m [16]. This is largely due to its many axes, each axis consisting of one gearbox that provides one degree of freedom. This description is highlighted in figure 2.7.
During the course of the project, measurements and analysis was done around axis 2 of the robot. The location of this axis is illustrated in figure 2.7. The reasoning behind this decision is due to the fact that the robot encumbers this axis the most during an operation.

2.2.2 Gearbox

The gearbox that convert the torque in axis 2, see figure 2.7, is a Nabtesco RV410F gearbox. The gearbox is a cycloidal gearbox, with a design that is strong and compact. It has a motion control which is a demand due to the robots required and precise accuracy. This comes from its mechanism to reduce the speed and get a great ratio, resulting in high gearing capabilities. Figure 2.8 shows how the mechanism works. When the input shaft rotates, the eccentric roller bearing also rotate. The cycloidal disk that is driven by the eccentric roller bearing will also revolve around the internal pins. When the input shaft has rotated one rotation, the cycloidal disk has revolved around one internal pin step. From the cycloidal disk, the motion is transmitted to the output shaft through the carrier pins [17] [18].
2.2. Hardware

The Nabtesco RV410F gearbox differ slightly. Instead of that the input shaft transmit the motion directly to the cycloidal disk through the eccentric roller bearing there is a gearing to three gears as can be seen in figure 2.9. These gears are mounted on a respective eccentric bearing shaft and then act as the input shaft in figure 2.8.

![Figure 2.8: The cycloidal gearbox function [17]](image)

The gearbox has two cycloidal disks that have an off phase with 180 degrees, which means that when the gear on the eccentric bearing shaft rotates one rotation, the
cycloidal disks will generate two pulse. The frequency of one gear mesh will therefore be double the rotation speed. The gearbox also includes three eccentric bearing shafts, they have an off phase to each other with 120 degrees. This can be seen in figure 2.10 below.

\[\text{FIGURE 2.10: The off phase of the cycloidal disks}\]

Due to the eccentric shafts being off phase, the pulse generated by the eccentric bearing shaft will occur with an off phase with 120 degrees. This results in that when the cycloidal disk revolves around one internal pin, the frequency will be six times that speed. Two pulses due to the fact that there are two cycloidal disks with 180 degrees off phase, and three pulses due to the eccentric bearing shafts off phase with 120 degrees.

2.3 Bearings

In the hypo-cycloid gearbox constructed by Nabtesco, there are three different types of bearings; Tapered roller bearing (TRB), angular contact ball bearing (ACBB) and cylindrical roller bearing (CRB). This section will describe these different bearings and what sets them aside from each other.

2.3.1 Tapered roller bearing

A Tapered Roller Bearing (TRB) have a cone shaped inner and outer raceway. The roller elements are tapered to adjust the raceways. This geometry of the rollers permits the bearings to manage higher load capacities compared to an angular contact ball bearing (ACBB), according to SKF’s product catalog “Tapered roller bearings” [19]. TRBs can carry axial loads in one direction and are therefore often installed in pairs to carry loads in both axial directions [19].

2.3.2 Angular contact ball bearing

An Angular Contact Ball Bearing (ACBB) have asymmetric inner and outer races and use the balls as rolling elements. ACBB is constructed to carry loads in radial and one axial direction [20]. The amount of load capacity depends on the angular contact. With an increasing angle contact, the possibility to carry higher axial load increases. Due to only being able to carry one-way axial load, ACBBs is often installed in pairs which results in that they can carry loads in both axial direction [20].
2.3.3 Cylindrical roller bearing

A Cylindrical Roller Bearing (CRB) is designed with cylinders as rolling elements. The contact between the cylinders and the raceways is a line contact and it can therefore withstand more load compared to spherical rolling elements. This permits the bearing to support large radial forces and the bearing is also suitable for high speed [17].

2.4 Bearing vibration frequencies

Bearings are vital parts in several machines today, therefore it is important to foresee if any defects are starting to develop. Defects can occur from fatigue, wear, poor installation, improper lubrication and occasionally manufacturing faults. These defected bearings can be foreseen by an analysis of the bearing vibration frequencies. To assess if a bearing is operating at critical levels, it is analyzed with the fundamental defect frequencies. If there is an irregularity in the raceway surface or an impact on the rolling elements, these fundamental defect frequencies will occur when the bearing rotates. These fundamental frequencies are dependent on the diameter, pitch diameter, number of rolling elements, contact angle and the shaft speed [21].

The pitch diameter $D_p$ is the diameter between the centers of the rolling elements which can be seen in figure 2.12. For the ball and roller element the pitch diameter can be calculate with equation (2.3) below, where $D_m$ is the outer raceway diameter and $d_m$ is the inner raceway diameter [21].

$$D_p = \frac{D_m + d_m}{2}$$  \hspace{1cm} (2.3)

For the tapered roller elements, the pitch diameter is also from the roller central. However, due to the conical geometry which can be seen in figure 2.11, the pitch diameter $D_p^*$ is calculated as equation (2.4) describes [22].
\[ D_p^* = D_p + \frac{1}{2} (D_m - d_m) \tan \left( \frac{\beta_i + \beta_o}{2} \right) \tan \left( \frac{\beta_o - \beta_i}{2} \right) \] (2.4)

### 2.4.1 Gear wheel frequency

When calculating the fault frequency for the cycloid disk, the running speed, gearing and the fact that the gear wheels revolves with the cycloid disk, have to been taken into account. This led to the equation (2.5):

\[ F_c = \left( 1 - \frac{G_m}{G_s} \right) \times \frac{1}{G_c} \times \frac{G_m}{G_c} \times \frac{S}{60} \] (2.5)

Table 2.1 clarifies the variables used in the calculation of the fault frequency and equation (2.5).

**Table 2.1: Variables to calculate fault frequency on cycloidal disk**

<table>
<thead>
<tr>
<th>Variables</th>
<th>Description</th>
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<tbody>
<tr>
<td>Gm</td>
<td>Tooth on motor shaft</td>
</tr>
<tr>
<td>Gg</td>
<td>Tooth on gear wheel</td>
</tr>
<tr>
<td>Gc</td>
<td>Tooth on cycloidal disk</td>
</tr>
<tr>
<td>S</td>
<td>Running speed</td>
</tr>
</tbody>
</table>

### 2.4.2 Fundamental frequencies

There are four fundamental fault frequencies connected to the bearing, these are shown in figure 2.12.
Fundamental Train Frequency (FTF), this frequency occurs when there is a defect on the cage of the bearing and is explained by [23]:

\[
FTF = \frac{S}{2} \times \left[ 1 - \left( \frac{Bd}{D_p} \times \cos(\Theta) \right) \right] \tag{2.6}
\]

Ball Spin Frequency (BSF), this frequency occurs when there is a defect of the rolling element. When this defect occurs it can result in two pulses each revolution, one at each contact surface and double the frequency. It is explained by [23]:

\[
BSF = \frac{D_p}{2Bd} \times S \times \left[ 1 - \left( \frac{Bd}{D_p} \times \cos(\Theta) \right)^2 \right] \tag{2.7}
\]

Ball Pass Frequency of the Outer race (BPFO), this frequency occur when there is a defect on the outer race and is explained by [23]:

\[
BPFO = \frac{Nb}{2} \times S \times \left[ 1 - \left( \frac{Bd}{D_p} \times \cos(\Theta) \right) \right] \tag{2.8}
\]

Ball Pass Frequency of the Inner race (BPFI), this frequency occurs when there is a defect on the inner race and is explained by [23]:

\[
BPFI = \frac{Nb}{2} \times S \times \left[ 1 + \left( \frac{Bd}{D_p} \times \cos(\Theta) \right) \right] \tag{2.9}
\]

When analyzing the bearing vibration frequencies, if a fundamental frequency and their harmonics occur repeatedly on frequency spikes it is probably a defect in the bearing [21].


2.5 Signal Processing Methods and Statistical Tools

2.5.1 Spectral Kurtosis

By utilizing spectral kurtosis (SK) as a statistical method, one can indicate how a signal is distributed by comparing it with a Gaussian distribution (normal distribution). This results in a statistical tool which can illustrate non-Gaussian distributed components in a signal and their location in the frequency domain [24]. The figure 2.13 below illustrates the different stages of kurtosis and the phenomenon that occurs.

![Figure 2.13: Indications of different kurtosis [25]](image)

As figure 2.13 demonstrates, there is no kurtosis if the signal has a Gaussian distribution. However, if the signal has an emerging peak, the kurtosis value is greater than zero and is recognized as a leptokurtic distribution. In the last case scenario, the kurtosis value is less than zero and is referred to as a platykurtic distribution. This often occurs during fixed deterministic signals, such as sine or square waves [25].

Spectral kurtosis is an effective processing method in filtering out white noise and is predominantly used in combination with other signal processing methods to identify abnormalities in the Gaussian distributed spectrum. Thus, resulting in a signal processing method that can indicate leptokurtic distribution in a measurement that would otherwise obstruct the evaluation of the signal. Leptokurtic distribution is a sign of a damaging event to the object and/or material in question [25], making it a contributing factor to the vibration condition monitoring.

2.5.2 Enveloping

The procedure of enveloping a signal is started by processing a time waveform signal, filtering out unwanted frequencies that is not within the requested bandwidth, resulting in a denser spectrum with less undesired clutter. The next step is to pass the signal through a rectifier, making the signal solely positive by taking the absolute value of the data, making it easier to detect abnormalities in the spectrum. Sequentially, to ensure there is no clutter within the wanted bandwidth, a low pass filter is applied to eliminate the inner sidebands of the signals. A Fast Fourier Transform
is finally exercised to present the fault frequencies within the spectrum and where they are located in the domain.

### 2.5.3 Spectral Auto-Correlation

The Spectral Auto-Correlation (SAC) is based on Auto-Correlation (AC) and The Fast Fourier Transform (FFT). The signal is first correlated and then calculated with FFT which will be explained in this chapter.

#### 2.5.3.1 Auto-Correlation

To get a better understanding how AC works, figure 2.14, 2.15 and 2.16 below, shows the fundamental steps of the procedure. The signal that is correlated is just a random sine wave and AC is used to investigate what frequencies correlate in one signal.

As can be seen in figure 2.14, the same signal is shown parallel but in different phases. When the correlation starts, the signal below begins to move forward meanwhile a comparison is made with the identical signal on top. The graph in the bottom is the result of the AC and shows how the signals correlated with each other. The measurement increases in amplitude when the signal below approaches the same phase as the signal on the top.

The first step on the left hand side of figure 2.15, shows the two signal in phase with each other which results in the peek in the AC graph. When the signal below continues to move forward, the correlation decrease.
Chapter 2. Theory

In figure 2.16, the whole correlation graph is shown. Every peak in the correlation graph shows where the peaks in the two signals is in phase. The more the two signals approach each other, the more the AC graph will increase in amplitude. This entails that pulses that repeat will correlate strongly and pulses that do not repeat can be seen as noise. This noise will not correlate during the whole procedure and will be reduced. The MATLAB script for the AC and the generated plots, can be given on request.

2.5.3.2 Fast Fourier Transform on Auto-Correlation

To further investigate in the AC signal methodology, the FFT is used in combination. What is interesting with this procedure, is the useful application when searching for possible defect frequencies. If there is a defect frequency, it will be repeated and can be seen as peaks in the AC graph. To find out which frequencies are located in the AC graph, the FFT is used. An example can be seen in figure 2.17 where an FFT is made from the AC graph that is shown in figure 2.16. There are three frequencies that is repeating at 7.5 Hz, 16.25 Hz and 127.5 Hz.

This can be compared to an FFT on the time waveform from the same signal, as can be seen in figure 2.18.
2.6 Production Simulation

The robotics of today have systems that are concentrated on the safety for the environment and shuts down if it is overloaded or is about to collide with its close surrounding [27]. The opportunity to integrate the already built in safety system with an adequate condition monitoring program, opens up the possibility for a truly self-sufficient machinery that has the capability of reducing consequential failures. Condition monitoring is a useful tool to reduce unplanned stops in a production setting and is considered a common practice in many areas of today’s industry. One area where condition monitoring has not managed to establish itself, is to the non-cyclostationary applications, such as robotics. The reason behind this predicament is due to the irregular operation pattern which generates unanticipated vibration noise. Since vibration analysis is the predominant analysis method in condition monitoring, this complicates and obstruct the evaluation of the condition of the machinery. However, this research report wants to illustrate the benefits of successfully integrate condition monitoring in operational industrial robots and compare the efficiency to a traditional production line without this monitoring service. Therefore, the researchers together, with their supervisors, decided to design a production simulation in the project, which can highlight the possible advantages of continuous

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FIGURE 2.18: Fast Fourier Transform on the waveform

When utilizing the AC before the FFT, more noise can be reduced and frequencies that repeats will occur as clear peaks in the FFT.

2.5.4 Spalling

Spalling is a wear mechanism that occurs from a fatigue. When two loaded surfaces come in contact the highest shear stress is not on the surface, but just below the contact area. This create cracks under the surface that develops with the fatigue. When the cracks have grown enough, the strength in the material decreases. The material surface above the cracks is released as flakes which is called spalling. This create a pit in the surface and particles in the lubrication. In some case the pit starts in one position and then progress outwards, which is called the "cyclone" effect due to its form. [26]
condition monitoring with zero downtime, enabling the opportunity to pro-actively schedule planned maintenance before complete failure and production stops.
Chapter 3

Method

3.1 Spectral Auto-Correlation and Fast Fourier Transform

This section presents how the Spectral Auto-Correlation was developed and how the data was analyzed.

3.1.1 Background to Spectral Auto-Correlation

To get a more trustful result and the possibility to prove it, there was an interest in analyzing the data with more than one method. A research was done with the focus on analyzing cyclo non-stationary signals. Spectral correlation density was found in article [28] and [29], the method was investigated and found useful. In the article they show that spectral correlation density made it possible to find defect frequencies from a signal with varying speed, by utilizing defected bearings and gears in a test rig. The result was present in a 3-dimensional graph with frequencies, orders and amplitude. From further investigations, it is sufficient enough to look at orders or frequency and amplitude when evaluating these measurements. Furthermore, the density calculations in spectral correlation density was not deemed necessary for this application, which made the calculations less complex and from that the Spectral Auto-Correlation was developed. The data was sampled in orders due to the changing speed but could be converted to frequency. That made it possible to see the result in both orders and frequency.

3.1.2 The Procedure

To analyze the signal with SAC and FFT the data in form of time signals, the samplings had to be transferred from the Database in SQL-server to MATLAB. This was made with an ODBC connection that made it possible to connect to a SQL-server through MATLAB. This MATLAB script can be provided upon request. Time signals were calculated for each day as explained in 2.5.3 to get the SAC and as explained in 2.1.2.2 to get the FFT. All the SAC and FFT were then set up in a time label as can be seen in figure 3.1 and figure 3.2.
To be able to compare the calculations and set up trends that could be analyzed with the goal to find some pattern, the cycle speed was set to different small span. The trends that were analyzed were the spectral lines, root mean square (RMS) at some range of hertz and the spectral diagram.

### 3.1.3 Spectral lines

These were analyzed separate and also together. It was done by calculating the RMS value for each spectral line and the first sideband of the first spectral line. They were plotted in a graph to see how they change over time. The total RMS value for all the spectral lines was also calculated and plotted. In this case there was also an exponential smoothing, see chapter 2.1.2.4, on the total RMS value plotted in the same graph.
3.2. Vibration Analysis

3.1.4 Rout Mean Square

To analyze how a peak or peaks in different frequency ranges change over time, the RMS was used, see section 2.1.2.5. The analyzed peaks were gear mesh frequencies and their harmonics. Analysis in different frequency range was made to a large extent to see if there was any change in the signals over time.

3.2 Vibration Analysis

This section describes the procedure when analyzing vibrations through SKF’s analytical measurement program @ptitude Observer and what factors that were analyzed.

3.2.1 Gear Meshing Frequency

Gear meshing Frequency (GMF) is the phenomenon where two different gears mesh together, creating a frequency which is categorized by its sidebands and harmonics. Sidebands, a result due to amplitude modulation (AM), is recognized as symmetric peaks around the GMF as seen in figure (3.3).

Harmonics on the other hand, depends on the impulses generated when gear teeth of one gear wheel are coming into contact with teeth of the mating gear wheel. This appears at 2x GMF, 3x GMF, 4x GMF and so on, this feature is illustrated in figure (3.4).
Figure 3.4: Harmonics of the gear mesh frequency

As figure (3.4) shows, 1x represents the gear mesh frequency or the keynote if you like. The harmonics appear on peaks depicting two times the GMF all the way to the eleventh harmonic.

3.2.2 Tooth Wear

Tooth wear, a result of continuous fatigue, will be recognized in the spectrum as an increase of sidebands, both in the amount and amplitude [30] [31]. Another giveaway is when the third (3x) harmonic of the gear mesh frequency increase in amplitude over time [30].

3.2.3 Hunting Tooth Frequency

Hunting tooth frequency is the circumstance when two specific teeth mesh, creating uneven and localized wear. This occurrence is of a low frequency and is experienced as a growling noise in practice [32]. When analyzing the measurement in spectrum analysis, look for an abnormal high peak in the low frequency domain.

3.2.4 Cracked or Broken Gear Tooth

The best way to indicate a cracked or broken gear tooth, is to utilize the time waveform analysis. If the bad tooth is recurring in the measurement in the form of displaced amplitudes, then it is an indication of a damaged tooth. Even though time waveform is the foremost instrument in detecting cracked or broken teeth, spectrum analysis has some indications towards these events as well. In the spectrum analysis, the gear natural frequency should be of a higher amplitude along with 1x sidebands of the damaged tooth [33].

3.2.5 Gear Misalignment

Gear misalignment occurs whenever shafts, couplings or bearings are not properly adjusted around their centerlines. This incident is particular bad since the misalignment causes the bearing to carry a higher load than it was designed for, causing a
3.2. Vibration Analysis

bearing failure due to fatigue. Gear misalignment can be detected by a high (2x) harmonic [34], illustrated by figure 3.5.

![Figure 3.5: A strong indication of misalignment](image)

Whenever the vibration amplitude is at or below 50% of the gear mesh frequency (1x), the misalignment is often considered tolerable. However, misalignment occurring between 50%-150% of the GMF, is an indication of prospective damage to the bearing. Every measurement above this threshold are consider sever cases of misalignment [35].

3.2.6 Looseness

Looseness may arise from different causes, poor mounting, defect or just simply missing components. Either way, a scenario with inefficient tightened parts may result in detachment or damage to the overall system. It is therefore important to observe tendencies of looseness in condition monitoring.

Looseness displays the harmonics of the gear mesh frequency with a high amplitude, greater than the keynote [35]. Harmonic (2x), (3x) and (4x) has often a high amplitude peak and is often a strong indication of looseness.

3.2.7 Gear Eccentricity and Backlash

An indication of eccentric gears is often the increase in amplitude of the sidebands of the gear mesh frequency. The characteristics of this incident is the development of one bad sideband, instead of the more recurring family of sidebands [36]. Gear eccentricity is also known to cause the gear mesh frequency, as well as the third (3x) harmonics, to increase in amplitude. As the title indicate, eccentric gears may also result in a backlash, causing an amplitude peak at the gear natural frequency (GNF).
Chapter 3. Method

3.3 Accelerated testing of the robot gearbox

This section will reveal the methodology of stressing the robot up to the breaking point. In order to ensure that the robot is deteriorating, the machinery is pushed beyond the integrated high-load safety system. In doing so, the equipment is overloaded and forced to manage with tensions outside the recommended operation and safety protocols. However, all the safety precautions were implemented before the stressing of the machinery began, in order to preserve a safe working environment. In practice, the robot will initiate an emergency stop whenever the duty factory is too high. Meaning that the robot’s engine get overburden and triggers its integrated heat sensors. Whenever this interruption occurs, an immediate startup of the running sequence was commenced to ensure further wear.

The running sequence of the robot has been consisting of a swinging pattern with its arm fully extended, swinging back and forward with a three second stop at each end. It has been important for the project to be able to run the experiments at the same speed as the previous master thesis project, this in order to evaluate and compare new to old data. Therefore, when overburdening the robot, the primary parameter that has been tampered with were the stops at each end. Thus, leading to an increased frequency of the swinging pattern and workload for the robot.

At the later stages of the project the speed was changed to guarantee a result that could be related to the robots deterioration and wear. This decision was taken when the participants considered that the data was sufficient for an analytic evaluation that could be associated with a potential fault. The first stress test was commenced with the help of personnel on location, the experiment was conducted as table 3.1 refer.

<table>
<thead>
<tr>
<th>Attempt (No.)</th>
<th>Speed (Cpm)</th>
<th>Top Speed (Cpm)</th>
<th>Pause (s)</th>
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</thead>
<tbody>
<tr>
<td>No. 1</td>
<td>2000</td>
<td>2500</td>
<td>-</td>
</tr>
<tr>
<td>No. 2</td>
<td>2000</td>
<td>2500</td>
<td>0.5</td>
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<tr>
<td>No. 3</td>
<td>2000</td>
<td>2500</td>
<td>3</td>
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<tr>
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<td>0.5</td>
</tr>
<tr>
<td>No. 5</td>
<td>2000</td>
<td>2250</td>
<td>0.5</td>
</tr>
<tr>
<td>No. 6</td>
<td>1800</td>
<td>2500</td>
<td>0.5</td>
</tr>
<tr>
<td>No. 7</td>
<td>1000</td>
<td>1250</td>
<td>3 &amp; 0.5</td>
</tr>
<tr>
<td>No. 8</td>
<td>1400</td>
<td>1750</td>
<td>3 &amp; 0.5</td>
</tr>
</tbody>
</table>

During the first experiment the robot started to show indications of deterioration, initiating the high-load safety system whenever the running sequence was tampered with. At this point of the project, the experiments were conducted by personnel at the location on directives from the researchers. But since the condition of the robot started to worsen, the experiments started to require more and more attention. Therefore, the next stress test demanded the researchers to be on location in order to strain the robot even further. The Gothenburg Experiment had the goal to completely exhaust the robot. The parameters of the experiment are highlighted in table 3.2.
3.3. Accelerated testing of the robot gearbox

Table 3.2: The Gothenburg Experiment

<table>
<thead>
<tr>
<th>Attempt (No.)</th>
<th>Speed (Cpm)</th>
<th>Top Speed (Cpm)</th>
<th>Pause (s)</th>
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<td>No. 2</td>
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<td>2500</td>
<td>2</td>
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<tr>
<td>No. 5</td>
<td>2000</td>
<td>2500</td>
<td>2 (In One Direction)</td>
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<tr>
<td>No. 6</td>
<td>2000</td>
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<tr>
<td>No. 25</td>
<td>2000</td>
<td>2500</td>
<td>-</td>
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<tr>
<td>No. 26</td>
<td>5000</td>
<td>2500</td>
<td>-</td>
</tr>
</tbody>
</table>

After these tests, the decision to stop the robot was made. The sound from the robot and the fact that the internal safety system had activated several times, was the foundation for this decision. If further tests would have been done there had been a risk for total failure which had destroyed the possibility to find the where the failure had occurred and propagated.
3.4 Dismantling the Gearbox

In order to determine the underlying cause for the breakdowns and establish the severity of the problem, the gearbox was removed from the robot for further inspections. Figure (3.6) illustrates the absent gearbox and its attachments to the IRB 6600 (2.2.1).

Once removed, the gearbox was meticulously examined for any damage or wear that could affect its performance during an operation. Figure 3.7 depicts the gearbox in its fully assembled condition. From here, one layer at the time were removed in order to study the interior of the gearbox.
3.4. Dismantling the Gearbox

Figure 3.8 show the gearbox without the lid, exposing the inner components. In this picture, one can find one of two ACBB-bearings located in the gearbox. Located in the outer rim of the gearbox, the ACBB-bearing enables the rotation of the gearbox against the stationary lid that protects the sensitive parts of the apparatus. Through the gearbox there are three eccentric bearing shafts with one gear each that transmit the torque from the input shaft to the eccentric bearing shafts, each fitted with two CRB and TRB-bearings. The torque is then transmitted from the eccentric bearing shafts to the cycloidal disks.

![Figure 3.8: The Gearbox without the lid](image)

These eccentric bearing shafts enables the cycloidal disks to rotate with 180 degrees off phase and can be seen in figure 3.9.

![Figure 3.9: The three eccentric bearing shafts](image)

Figure 3.10 shows the exposed base of the gearbox. Fitted with the remaining ACBB-bearing, the base offers a stable foundation that enables a robust mounting platform for the remaining gearbox. The ACBB-bearing allow the gearbox to rotate against the stationary foundation without creating any harmful friction.
The remaining components of the gearbox are illustrated in figure 3.11, showing the capability of the high gearing operations. For each rotation of the gearwheel shafts, the gearbox revolves one step around the outer raceway.
3.5 Production Simulation

To get a trustful result, the authors choose to simulate a robot cell from SKF’s production line. The robot cell’s configuration was received from a maintenance manager at SKF with some basic information. The layout of the Robot cell can be seen in picture 3.12 below.

![Diagram of robot cell at SKF](image)

**Figure 3.12: Layout for robot cell at SKF**

The robot cell consists of five processes, one buffer and two robots that move the object through the line. Due to the purpose with the simulation, the authors wanted to know how much more efficient the robot cell would be with a condition monitoring system. In order to do so, the researchers created two identical robotic cells, one with condition monitoring and one with active failures and production stops. According to data received from SKF, they have scheduled maintenance stops every fifth week for planned services and examinations. Therefore, in an ideal world, the robot cell with continuous condition monitoring should have the aspiration to schedule any maintenance operations during these planned production stops. This ambition of zero downtime is therefore correspondingly reflected in the production simulation, resulting in the robot cell with condition monitoring to operate without any unexpected stops. Schedule hours, stop time, amount of failures, Mean Time Between Failure (MTBF), Mean Time To Repair (MTTR) were collected and received by SKF and was represented by the time frame between September 2017 to February 2018.

Figure 3.13 below shows the simulation of the two robot cells. The cell to the left is operating with zero downtime and condition monitoring, meanwhile the cell to the right is operating under “normal circumstances” and active production stops.
Due to inadequate information concerning the process times for each of the stations, the simulation is running on hypothetical operation times. However, since both of the robot cells will be compared with each other in order to determine which is more efficient, the process time will have a negligible impact on the end result as long as both cells have the same hypothetical in-data.
Chapter 4

Analysis

After the tests were completed and the gearbox was removed, the components were analyzed, which will be presented in this chapter.

4.1 The lubrication

During the dismounting of the gearbox the lubricant was analyzed. As can be seen in figure 4.1 below, the lubrication is dark and not in a good condition. The poor condition of the lubricant could be the reason of a defect in the bearing [37] [38]. It is therefore important to have the condition of the lubrication in mind when a defect is detected.

![Figure 4.1: Emptying of lubrication](image)

sa sadw
4.2 Analyzing the Components

In figure 4.2 below, the dismounted gearbox can be seen. The parts were cleaned so the surface was clear and easy to analyze. The parts were then analyzed to see if any wears could be detected.

![Figure 4.2: The Components of the Gearbox](image)

4.2.1 Angular Contact Ball Bearings

Due to the small contact area between the rolling elements and the raceways, ball bearings tend to have lower load capacities compared to other bearings [39]. Due to this fact, a thorough investigation was made, both on the rolling elements and the raceways. Figure 4.3 highlights the angular contact ball bearing (ACBB) and the outer raceway ready for inspection.

![Figure 4.3: Evaluation of the ACBB bearing and the outer raceway](image)
Firstly, the outer raceway was examined in order to detect any localized wear or damage, the rolling elements were then sequentially removed from the inner raceway. The inner raceway was then exposed to the same methodology before turning the attention towards the rolling elements. Figure 4.4 showcases the inspection of the rolling elements of the ACBB bearing.

However, upon examination of the ball bearings and the raceways, no apparent sign of damage or wear could be found.

4.2.2 Cycloidal Disks

When analyzing the cycloidal disks apparent wears were detected, which can be seen in figure 4.6. The defects were found on several of the teeth on both of the disks. One interesting point was that there were only defects in one direction. The reason behind this finding could be that the load is higher in one direction. The defect can be seen as a spalling wear due to its shape, see 2.5.4. The spallings are initiated on that the cycloidal disk teeth and the internal pins are pressed in contact. The spalling starts in the middle of the teeth and then progress out. The more the defect grow it transfer the pressure to the edge, which explain the oval shape of the defect and can be seen in figure 4.5.
Even though this is a model of an CRB bearing, the inner raceway has teeth which the internal pins revolve through and are therefore seen as gear teeth when analyzing the sampling data. From a defect frequency point of view, the cycloid disk can thus be seen as a gear with a mesh frequency calculated as chapter 5.3 and equation (2.5) describes.

To calculate the fault frequency for these cycloidal disks the main fault frequency, that can be seen in chapter 2.4.2, could not be used. Due to the design, the fault
frequency had to be calculated with regard to the gearing and the running speed of the motor.

The cycloidal disk revolves with one internal pin when the gear wheel rotates one rotation, see chapter 2.2.2. This and the knowledge that the running speed is affected of the revolving cycloidal disks due the gear wheels rotates with the cycloidal disks, makes it possible to calculate the fault frequency.

The whole construction with the bearings, gears and gearing is defined using the aptitude Observer Machine Parts. The frequency for the gear wheel can therefore be plotted. Figure 4.7 shows a spectrum where the gear wheel frequency is plotted as "gear wheel3" with its harmonics. It is clear that the sixth harmonic is dominant. This can be explained by the phase offset of the three gear wheel shafts and the fact that there are two cycloidal disks. This is explained in chapter 2.2.2.

![Figure 4.7: Spectrum of the gear wheel and its harmonics](image)

With this analysis it is clear that there is a connection between the detected defects and the high spikes in the spectrum. When the fault frequency is analyzed with SAC it is clear that there is a high spike at the sixth harmonic as well, as can be seen in figure 4.8. The figure also shows that there is a high positive sideband to the sixth harmonic. The sideband, also regarded as the amplitude-modulation Technologies [40] [41], is often occurring in rotating machines and is the fluctuation in amplitude due to the influence of another signal component called frequency modulating [41]. The distance between the sideband and the harmonic is measured to 1,55 Hz, which corresponds to one sixth of the fundamental fault frequency. This distance, between the carrier frequency of the sixth harmonics and its sidebands, is due to frequency-modulation [40] [42]. The common modulating-frequencies are turning speed or 1x vibration components, and the most recurring modulated frequencies are gear mesh and bearing tones [41]. Therefore, the researchers are positive that the distance (frequency modulating) between the carrier frequency and the sidebands is due to the gear mesh. This argument is based on the fact that the sixth pulse becomes stronger due to the gearbox consists of two cycloidal disks and three eccentric gear shafts.
FIGURE 4.8: Spectral Auto-Correlation of the cycloidal disk fault frequency
4.2.3 Eccentric Bearing Shaft

After being dismounted from the gearbox, one eccentric bearing shaft indicated for a potential wear. Figure 4.9 illustrates earlier mentioned bearing with bright lines over the rolling elements. After a careful inspection of the outer raceway, the researchers could exclude external faults and were therefore compelled to open up the bearings in order to establish the underlying cause.

Figure 4.10 provides a closeup of the pattern that indicated a fault on the inner raceway, all of the rolling elements were presented with the same material scarring. Since the outer raceway could be excluded as the originator of the problem, it was a necessity to open up the bearings mounted on the eccentric bearing shaft.
In order to examine the inner raceway, the bearings had to be dismounted. Each eccentric shaft was fitted with two CRB and TRB bearings which converted the input torque from the engine and enabled the high gearing sequence of the gearbox. Figure 4.11 illustrates the bare eccentric shafts ready for inspection.

Barely visible for the naked eye, a failure was detected on one of the bearing shafts. Figure 4.12 showcases a deformity that was detected only after deliberate examinations. Located on raceway number two (seen from above), the deformity led to a more thorough investigation with a Wyko 1100NT 3D optical surface profiler.

Figure 4.13 below, depicts a close up of the breach. Generated by the 3D optical surface profiler, the researchers were able to see the defect in a high resolution and could determine the cause of the problem. Indicated by the beach marks and the fatigue crack propagation, the underlying problem was determined to be a fatigue failure.
In order to establish the characteristics of the defect, a 3D plot was generated. With the help of figure 4.14, one can determine the dimensions of the fatigue failure.

**Figure 4.13:** Optical Surface profiling of the fatigue failure, with the rotation directions as the arrow illustrates.

**Figure 4.14:** 3D depiction of the fatigue failure, with the rotation directions as the arrow illustrates.

Furthermore, a surface profile was made on the affected area, highlighting the specific width and depth of the breach. This profile is illustrated in figure 4.15, where one can determine the width to 392,8 um and the depth to 7,2 um.
From this surface profiling one can also pinpoint the beach marks of the fatigue failure. Highlighted in the Y-profile of figure 4.15, one can locate three segments of the first incline in the spectrum. These segments represent the three beach marks that can also be seen in figure 4.13.
Chapter 5

Result & Discussion

5.1 Final stress test of the robot

During the final hours of stressing the robot, the speed and pauses in the operation sequence were altered with. The reasoning behind this decision, were to overload the robot to the maximum before dismantling the gearbox. The specific stressing method and what parameters that were changed can be found under chapter 3.3. Figure 5.1 illustrates the amplitude and speed alteration during the stress tests. Those periods where the graph appears linear are periods where the robot was stationary. The cause of this static behavior is due to the intervention of the robot’s integrated safety system, whereby the robot is forced into a nonoperational state. For more information regarding the integrated safety system, read chapter 3.3.

![Figure 5.1: Trend over the last time that the robot was in action.](image)

When the final stress test was commenced, the speed was returned to the original speed of 2500 cpm and was sequentially increased, which is illustrated in figure 5.1. The result of these tests were a rattling sound from the gearbox that became more distinctly at higher speeds. The robot developed a high frequency sound also, that did not exist in the beginning of the project. This noise together with the fact that the robot’s safety system had triggered multiple times, led to the decision to stop the testing for the evaluation of the gearbox. The gearbox was dismounted from the robot and opened up for further analysis.
5.2 Evaluation of the Cycloid disk with Observer

When assessing the damage of the cycloid disk, seen in figure 4.6, it became clear that the defect were related to a tooth wear. When consulting the theoretical implications of a tooth wear in a spectral analysis, it should indicate an increase in amplitude regarding the third (3x) harmonic and its sidebands, see chapter 3.2.2. The figure 5.2 below, illustrates one of the spectral analysis conducted during the research.

![Figure 5.2: Evaluation of tooth wear in the spectrum](image)

Thanks to @pitude Observer integrated calculation tool, observer had already appraised the fault frequency for the cycloidal disk. Pinpointed as Gear Wheel3, the harmonics were plotted in the spectrum to assess if the data could be related to the theory. An interesting observation is that all of the harmonics to the fundamental frequency were predominantly dominant regarding the amplitude, however the sixth harmonic were the amplitude peak that caught the researcher’s eyes. The reasoning behind this intriguing sixth harmonic can be related to chapter 2.2.2. Due to the gearbox design, two cycloidal disks with an offset of 180 degree generates two pulses per revolution, practically making the second harmonic the fundamental frequency. With this in mind, the sixth harmonic will act as the third harmonics for the new fundamental frequency, which corresponds well with the amount of eccentric gear shafts and complies with the theoretical commitments regarding tooth wear, according to chapter 3.2.2. Nevertheless, even though these peaks were higher in amplitude, they were missing the essential sidebands to be categorized as a typical tooth wear. Therefore, an evaluation of the data was done in MATLAB. By compiling the data from Observer a revision of the spectrum analysis was done in a form of a FFT-plot, showcased in figure 5.3.
5.3 Evaluation of the Cycloid disk with Matlab

Figure 5.3 illustrates the iconic sideband that is associated with tooth wear, further strengthen the case and credibility for being the underlying problem. In order to confirm the calculations made by Observer, a theoretical calculation was conducted and can be seen under chapter 2.4.1.

5.3 Evaluation of the Cycloid disk with Matlab

Due the fact that fundamental fault frequency for the cycloidal disk is the same frequency as the gear wheel frequency, equation (2.5) was used. The fault frequency is dependent on the running speed and will alternate with changing speed. Table 5.1 presents the fault frequencies for various speed.

<table>
<thead>
<tr>
<th>Running speed (CPM)</th>
<th>Fault frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2500</td>
<td>8.02</td>
</tr>
<tr>
<td>2600</td>
<td>8.34</td>
</tr>
<tr>
<td>2700</td>
<td>8.66</td>
</tr>
<tr>
<td>2800</td>
<td>8.98</td>
</tr>
<tr>
<td>2900</td>
<td>9.3</td>
</tr>
<tr>
<td>3000</td>
<td>9.62</td>
</tr>
<tr>
<td>3100</td>
<td>9.94</td>
</tr>
<tr>
<td>3109</td>
<td>9.97</td>
</tr>
<tr>
<td>3200</td>
<td>10.26</td>
</tr>
</tbody>
</table>

From the Analysis, see 4.2.2, the researchers came to the conclusion that it is relevant to inspect the sixth harmonic, which in this case means evaluating spectral lines
which is equal to six times the faulty frequency. When comparing the theoretical sixth harmonic with the frequency spikes in the spectrum, the researchers utilized MATLAB to create figure 5.5 and figure 5.6. These plots were sequentially used in the assessment of how the sixth harmonic had behaved during the project. Both spectra were sampled at a motor shaft speed of 3109 cpm. The theoretical sixth harmonic at 3109 cpm is located at 59.8 Hz, which is about three Hz higher than the spike shown in the spectrum. When comparing the theoretical fault frequency 9.97 Hz, from table 5.1 with the calculated result 9.69 Hz in figure 5.4, the deviation is approximately 0.28 Hz.

This margin of error is small and can be negligible. This is due to the fact that the precision to accurately match the fault frequency is not high enough to get a 0% deviation with the theoretical calculations. Measurement uncertainty of the fast-changing rotation speed may affect the result as well, due to the fault frequency is depending on the rotation speed. To get the fault frequency 9.69 Hz from the theoretical calculations, see equation (2.5), the rotation speed should be 3021 cpm, which results in a fault margin of 2.9%. The result of a small margin of error at the fundamental fault frequency, increase the margin of error six times at the sixth harmonic. In other words, a small deviation at the fault frequency will escalate the inaccuracy with higher harmonics and misrepresent the conclusion.

As previously mentioned, to see how the frequencies change over time and how the growing defect affect the spectrum, 3D graphs were plotted. The frequency label was set between 8 and 80 Hz to include the fault frequency and all the interesting harmonics. The 3D graph in figure 5.5, was constructed from a Spectral Auto-Correlation processing meanwhile figure 5.6 was shaped from a Fast Fourier Transform. On a few occasion, the graph appears to be linear, this is due to the robot being non-operational for various reasons.
5.3. Evaluation of the Cycloid disk with Matlab

FIGURE 5.5: Spectral Auto-Correlation with 3109 cpm over time with frequency span between 8-80 Hz

FIGURE 5.6: Fast Fourier Transform with 3109 cpm over time with frequency span between 8-80 Hz

With Spectral Auto-Correlation (SAC) the sixth harmonic and its positive sideband dominant the fundamental frequency, which results in the other harmonics being overshadowed and almost hard to recognize. With FFT the sixth harmonic and its positive sideband are dominant as well, but not to the same degree that the harmonics are obscured. Due to the fact that the sixth harmonic is the relevant spectral line to analyze, both of the methods are applicable and used in the evaluation of the fundamental fault frequency. In both methods it is possible to see that the amplitude is growing over time, with highest increase in the beginning of the sampling. Figure 5.5 showcases a steady increase in amplitude, even at the end of the sampling. This is due to the final stress test that the robot withstood which resulted an even more overloaded gearbox.

To analyze the sixth harmonic and specifically its positive sideband, trends with the RMS-value and exponential smoothing were created. Trends accumulated with
SAC can be seen in figure 5.7. Respectively, trends with the FFT processed data can be seen in figure 5.8. The registered RMS-value in the graph is the sum of the peak value and the closest spectral lines on each side.

In both methods the RMS value is almost doubling before the final stress. With SAC, the sixth harmonic and its sideband are increasing more constant compared with the FFT where both increase much more in the beginning of the sampling and then smooth out. To easier see the trend, figure 5.9 and 5.10 shows the trend with exponential smoothing of the RMS trend.
The trends are clear, in both methods the amplitude is increasing. However, when it comes to determine when the defect first occurred, it becomes a lot more complicated and harder to validate. According to the FFT where the amplitude is increasing steadily during the period between May and July, could be an indicator that a defect might have occurred. To strengthen this case, it would be necessary to have access to earlier data to see how the trend behaved before this increase. Unfortunately, the data that is presented in graphs is all the information this research has access to. Worth mentioning, the robot used for this project is a second-hand merchandise
with its life span already expended, so there is a possibility that the defect occurred long before the research project begun.

5.3.1 Possible wear development of the cycloidal disks

With the result from the analysis along with the damage on the cycloidal disk, the theories that confirm that the sixth harmonic is the point of interest and the indication of tooth wear due to a dominate sideband. The growing amplitude on the sixth harmonic and its sideband during the project gives an indication that it is advantageous to analyze these trends when monitoring industrial robots and its cycloidal disk.

The growing trend on the sixth harmonic and the defects on the cycloidal disks make this case highly interesting. The trend show an increasing amplitude about 170 days before the robot’s integrated safety system triggered and disabled the robot, see figure 5.11. With this information, the stop for maintenance and changing the gearbox could be planned well in advance.

In this research, different methods have been used and they all show the same result which make the case more truthful and, in the future, they can be used to complete each other. Due if the trend is followed in an early state when the cycloidal disk is intact, the trend should be more stable, hypothetical. So, when a defect initiates it may occur an interference in the pattern. with two different methods the possibility to detect this interference is higher.

After analysis and discussions with experts in the field, a hypothetical wear development of the cycloidal disks were concluded as follows:

**Step 1:** In the beginning when the robot was overloaded, the subsurface on a few cycloidal disk teeth were stressed and thus started to generate heat.

**Step 2:** The damage in the subsurface then developed to small spalling damage. The spalling happened in the highest stress areas, due to increased friction. This generated high amplitude vibrations.

**Step 3:** Due to increased friction, the spalling transferred the load to the other gears. The increasing spallings, subsequently increased the vibrations as well.

**Step 4:** After a while the spalling generalizes and the damage establishes. The extension to other gears does not fundamentally change the vibration pattern.

**Step 5:** The defective teeth entails and generate particles in the lubrication which spread the defect to even more teeth.

**Step 6:** When the robot was stressed even further, the vibrations and heat increased dramatically.
Figure 5.11 shows the trend of the growing sixth harmonic and the hypothetical theory of how the wear developed over time. The first two steps are when the wear initiates and the first spallings develops. The third is the transition to the establishment. The fourth steps is when the wear establishes on the teeth. The fifth and sixth steps are when the wear get critical and the load increase over its functional condition.

To strengthen this hypothesis, condition monitoring has to be done during a longer period where the cycloidal disks do not have any defects for sure in the beginning to see how the trend acts before the initiation.

5.4 **Cylindrical Roller Bearing fatigue failure**

Due to the current stage of the fatigue detected it is difficult to find signs of the defect in the sampled data, that could be trended and show how the defect developed over time. The appearance of the defect can also affect. Due the rollers on the CRB have a wide interaction surface, it is possible that it does not create a pulse high enough to be detected when it rolls over the small defect on the inner raceway. Furthermore, this fatigue failure could ultimately be the result of the gear spalling generated on the cycloidal disks. Due to the release of large material particles in form of spalling, it is a high possibility that these particles interfered with the CRB bearing after it polluted the lubrication. As chapter 4.1 demonstrate, the lubrication was not in a
good condition, which further strengthen this theory. This, resulting in the rolling elements crushing the particles against the surface and generating the fatigue failure presented in figure 4.13.

To analyze the data the fundamental fault frequency for the CRB was calculated. Equation 2.9 from chapter 2.4.2 was used with equation 2.5 from chapter 2.4.1 in order to establish the fundamental fault frequency. In figure 5.12 the fundamental fault frequency and its six harmonics can be seen in the SAC as the red lines. The motor speed for this sampling is 3001 CPM and the fundamental fault frequency is 90,7. What can be analyzed is that the fourth harmonic is on a spike.

![Spectral Auto-Correlation of fault frequency for CRB](image)

**Figure 5.12**: Spectral Auto-Correlation of fault frequency for CRB

In figure 5.13 is the same sample as in figure 5.12 but without SAC. The fourth harmonic is on a spike in this case as well.

![Fast Fourier Transform of fault frequency for CRB](image)

**Figure 5.13**: Fast Fourier Transform of fault frequency for CRB

To see how the fourth harmonic develops over time a trend was produced with exponential smoothing from the FFT and can be seen in figure 5.14.
5.5. Misalignment

This graph shows an increasing trend for the fourth harmonic which could be an indicator of a wear. But due to the small defect it is hard to strengthen this case without any further investigations.

5.5 Misalignment

When initially analyzing the measurements in the project there were a lot of indications of severe misalignment, according to chapter 3.2.5. However, the gearbox seemed to be operate under normal circumstances, which raised a few questions. Figure 5.15, illustrates a sampling from 20th of July 2017. As the figure highlights, the second harmonic of the gear mesh frequency is more than five times than the fundamental frequency. This would have been a catastrophic failure according to the theory and chapter 3.2.5.
This investigation did not result in any answer why this sign occurs. The authors have discussed that it could be due to the construction of the gearbox where some of the shafts not only rotate through their own axis but also oscillate during their rotations. But there is no evidence that confirm that this theory.

### 5.6 Plant Simulation

This simulation compares how the robot cell works today with an ideally case where every damage can be detected with the monitoring system. The comparison was made to show how more efficient it is when utilizing the knowledge about the condition of the machines and robots. By considering one robot that have an availability of 99.3 percent it is easy to think that it not influences that much, but when everything is put together, the affect does become apparent. The result of a year production can be seen in figure 5.16. With a condition monitoring system, the production produce 227243 products compare with the production without condition monitoring that produce 220077 products. If the results are divided it shows an increment of the production with 3.25 percent. It may not sound that big, but when it is calculated with production of a year it makes a significant difference.
The production simulation also makes it possible to try different methods and production plans without changing the production in reality. This may be more useful if the whole production line is simulated instead of just a single robot cell like in this case.
Chapter 6

Conclusion

The defect in the robot gearbox that leads to a failure may occur a long time before it becomes critical. If this defect is detected in an early phase, the service stop can be planned. With a production simulation that compare this scenario, with and without condition monitoring, the result show an increasing productivity with 3.25 percent with condition monitoring in place.

The first step towards developing Robot Condition Monitoring by utilizing vibration analysis is made in this project, with successful results. A new method was developed called Spectral Auto-Correlation. The concept is to correlate the time waveform with itself and then process it through the Fast Fourier Transform to get a result in spectrum analysis, which enables further investigation.

An IRB6600 robot has been stressed to failure and monitored during this project. When the gearbox was dismounted and analyzed, defects on the cycloidal disks were found, that could be seen as tooth wear. By calculating the fault frequency of the cycloidal disk and analyzing that specific frequency in the spectrum, the sampled data resulted in a trend that showed a growing amplitude on the sixth harmonic and its positive sideband, which can be explained by the theory.

A small fatigue defect on the CRB was observed during visual inspection but since the defect was presumably in an initial stage, it could not be detected by the methods used in this master thesis project. Furthermore, this defect is believed to be the result of the spalling generated on the cycloidal disks.

This is the first step of condition monitoring of industrial robots. To succeed with a complete condition monitoring system that includes all parts of a machinery, there have to be more investigations and research within the subject. But this research has shown the potential use of vibration analysis for non-cyclostationary operations and condition monitoring for future use.
Chapter 7

Future Work

7.1 Condition monitoring by signal analyzing vibrations

This investigation has shown that condition monitoring by vibration analysis is an interesting method for condition monitoring of industrial robots. But further work to develop the method even more is necessary. Investigations regarding finding relevant cases where other parts in the gearbox are defected and then try to detect it through the acquired data, is a recommended course of action in order to enlighten the detection of potential wear. In this project the robot was operating with a straight arm in a half circle motion, this to load the gearbox in axis two to its max. It would be interesting to monitor the robot when it is working in a real case. That may cause different loading and result in other defects. The authors are united with the thought that condition monitoring by vibration analysis is a method that in future will be a useful tool to prevent unplanned stops. But the method has to be iterated and frame all relevant defects that may cause a stop before becoming truly efficient.

7.2 Other Methods

In a future work the authors think it had been interesting to investigate, in addition to vibration monitoring, condition monitoring by analyzing the temperature in the gearbox, the current and the lubrication condition. In these fields there are more previous work done which can be useful.

7.2.1 Current Condition Monitoring

By measuring the motor current, one could get an indication of the condition of the apparatus. For an example, a steady increase in resistance may be an indication of increased inertia, providing a useful insight that one or several components are actively deteriorating. Even though Current Condition Monitoring (CCM) might be a useful tool to detect eventual problems, it lacks the ability to detect the underlying cause. Therefore, the authors believe that CCM could be a useful subsystem in for a larger monitoring operation, combining several procedures to provide uniform information that the machinery is deteriorating.

7.2.2 Thermal Condition Monitoring

In order to increase the load of the gearbox, the previous master thesis project installed a cooling system around the motor. A consequence of this intervention was that the gearbox could now be stressed further, with elevated temperatures as a result. During the final stage of the test, the authors started to stress the robot in a greater extent. The integrated safety system in the robot started to switch off the
robot due to high temperature generated in the gearbox and the motor. This increase in temperature is possible not due to a damage or a wear, but ultimately the result of the increased overload. However, it is possible to use the data that the robot already logs and utilize the information in combination with measuring methods such as: vibration, thermal, current and lubricant condition monitoring. This methodology of evaluating all of the aspects of the robot, is considered a recipe of success regarding condition monitoring, according the authors.

7.2.3 Lubricant Condition Monitoring

The condition of the lubrication is also something that is interesting to investigate. If wear occurs, it may be possible to see evidence in the lubrication that could indicate the wear. The problem that the authors see with lubrication condition monitoring, is to analyze the lubrication while the robot is working and not only in conjunction with service.

7.2.4 Production Simulation

The production simulation that was developed in this project was a start that just looked at one robot cell to show the advantages with a condition monitoring system on industrial robots. A further work could be to extend the simulation to observe a line or a whole production. This includes more robots and machines and will make it possible to show the advantages in a bigger picture. With a production simulation over the whole production it is also possible to find bottlenecks and try solutions without any costs compared to changes directly in the production.
Bibliography


