Detection of tool wear in drilling based on axis position signals

Anders Hansson
Summary

Cutting operations are important and commonly used operations in the field of manufacturing. Automated machining is today commonly used in CNC-machines. One common drawback with automated machining is that the tool condition is challenging to predict which leads to a conservative tool replacement time. This leads to a low utilisation of the tool economical lifetime and an unnecessary high number of tool replacements. Methods for indirect continuous monitoring of the tool wear exist but usually require retrofitting of external sensors that can be both costly and also interrupt the machine operation due to the additional wiring. It is therefore of interest to investigate the possibility to use the, often high resolution, sensors already fitted in a CNC-machine to extract valuable data that can indirectly give an estimation of the tool condition.

This thesis work has, with attention to the X-, Y- and Z-position sensors, resulted in development of algorithms that show relations between tool wear and data acquired from these sensors. The algorithms operate in the frequency domain to determine changes in the dynamic response over the time of tool degradation.

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This master degree report, *Detection of tool wear in drilling based on axis position signals*, was written as part of the master degree work needed to obtain a Master of Science with specialisation in manufacturing degree at University West. All material in this report, that is not my own, is clearly identified and used in an appropriate and correct way. The main part of the work included in this degree project has not previously been published or used for obtaining another degree.

Signature by the author

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Date

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1 Introduction

Cutting operations are a major part of the processes used within the manufacturing industry. Drilling is, together with turning and milling, one of the major metal cutting operations. As the production time spent on cutting operations for a component during manufacturing can be considerable, it is often of interest to maintain a high material removal rate (MRR) which is often equal to high cutting speed. On the other hand, a high cutting speed might lead to faster degradation of the tool with more frequent, and time consuming, tool changes as result.

Unmanned cutting operations are today highly developed with computer numerical control (CNC) systems for managing the tool path and specially developed materials for suitable chip formation that reduces the need of supervision for detection of problems such as chip entanglement or tool breakage in the machinery. Monitoring of the tool condition is however not as well established in the industry, instead a conservative approach that might lead to limited utilisation of the tool economical lifetime is commonly used.

The industry often aims for a balance between high MRR, adequate surface finish, and a low number of required tool replacements. If a cutting tool is used after a certain wear level, there is a risk that the work piece is damaged. Sometimes a worn tool can cause heat generated damages to the material microstructure that makes it necessary to scrap an entire component to avoid early developed fatigue damages in the affected area. This fact often makes the industry to operate with a conservative approach when estimating the remaining tool life. The economic lifetime of the tools are therefore seldom utilised. One study points out that the spread in lifetime for 30 cutting tools from the same batch operated under identical conditions experience a spread of ~40% in the usable cutting time [1]. A conservative approach would then operate each tool for a fixed and shorter period of time than the tool that experienced the shortest lifetime during the test. This leads to a high number of non-utilised cutting time for the tools that in reality would be operative for up to 40% longer time. Fully unmanned production with high utilisation requires a system for tool wear monitoring and tool rupture determination.

Studies for determination of tool degradation have been ongoing for many decades to avoid unnecessary tool changes and achieve a high utilisation of the tool in use. The tool wear determination can be carried out either by direct measurement, by the naked eye, microscope or camera, or indirect by analyses of other parameters related to the cutting operation [2]. Special equipment for the purpose has also been developed and is widely available and used in the market.

Finding a suitable and simpler alternative to an external sensor system is desired; hence, potential alternatives based on the machine internal sensors are studied in this thesis.
1.1 Aim

Tool degradation is today usually determined by implementing external sensor systems with e.g. piezoelectric elements or strain-gauges that measure the cutting forces. Such systems require a high cost for implementation and might lead to reduced operability of the machine as the sensor system has an influence on the machine original design.

The aim for this thesis work is to investigate the possibility to utilise the sensors already implemented in a CNC-operated drilling machine. The work is carried out with attention to the machine tool’s internal linear axis position sensors with external sensors for potential verification. Focus is kept in finding suitable ways to analyse the collected signals by means of frequencies, amplitudes and other static or dynamic variations.

It is desired to gain understanding in the possibility to utilise the machine internal sensors for determination of tool degradation over time as well as the potential, in short notice, to pick up indication of an upcoming sudden tool failure.
2 Background

In general, the degradation of a cutting tool can be divided into three phases where the evolution of the dynamics generated from the cutting operation can be reflected and defined. The first phase is the breaking-in phase followed by a phase of wear stabilisation and finally a phase of wear acceleration [1]. The schematic evolution of these stages are visualised in Figure 1. The schematic presentation is based on the data collected and analysed in [1] where an accelerometer is used to pick up the dynamics from the cutting operation. The different measured parameters or methods are listed and described. Each sub-category that has been studied, is presented with a summary as well as a brief description in how the signals can be collected.

Figure 1 – Schematic presentation of the different phases of drill degradation. 1 is the breaking-in phase, 2 is the wear stabilisation phase and 3 is the wear acceleration phase. a and b denote the two breaking points where change in gradient occur.
2.1 Drilling behaviour in general
Drilling of a through hole can generally be described by four stages as seen in Figure 2 where stage 1 is the tool engagement when the tool tip is pushed towards the work piece with no cutting speed at the centre until the cutting operation starts and the tool is eventually fully engaged at stage 2. Stage 3 is the continuous cutting operation until the tool tip start exiting the work piece and is fully through at stage 4.

![Figure 2 – Schematic description of drilling a through hole.](image)

The torque and power relation for a representative drilling operation are presented in Figure 3 where it is seen an increase in thrust force during engagement until cutting starts and thereafter require increased torque until full engagement. After the continuous drilling operation the torque and thrust requirements are reduced until the tool is fully through.

![Figure 3 – Example of torque-power relation during drilling of a through hole.](image)

2.2 Existing methods for tool wear determination
One method used for determination of the tool degradation is to establish a window of operation where the power/torque and thrust force are considered acceptable, op-
operation outside this window indicates a tool wear exceeding a level suitable for tool replacement [3]. However, this method usually requires external sensors for determination of the required parameters.

Figure 4 shows an example where the measured parameters from one new and one worn tool are presented, it is seen that the worn tool operates outside the defined window of operation and should therefore be replaced.

![Figure 4 – Example of window of acceptable cutting parameters, data from a new (blue) and highly worn tool (red) are presented.](image)

Below is described some of the parameters possible to measure related to indirect determination of tool wear.

### 2.2.1 Cutting forces

It is considered natural to measure forces when aiming for indirect determination of tool wear as a worn tool is expected to require higher forces compared to a sharp one. The reason for this assumption is the increased friction between tool and work piece with more wear of the tool cutting edge. These measurements do however normally require additional measurement systems to be integrated to the machine as most machines in the marked do not have these features built-in from factory.

#### Spindle Torque

Several researchers suggest that the spindle torque, and hence cutting force, can be used to reflect the tool degradation over time, especially when considering relative reference measurements [2, 3, 4, 7, 9]. One drawback for this kind of measurement is that the work piece hardness is crucial. Deviations in hardness between the incoming materials have to be within 5% of the mean hardness for generating a baseline of the drilling operation, this is considered to be difficult to achieve in industrial castings. It is recommended that torque measurements are used for condition monitoring only if the work piece material is of very close tolerance with regards to hardness [4]. The direct measurement of spindle torque is often carried out with special equipment mounted between the machine spindle and the drill holder. The equipment determines the torque with e.g. strain gages or piezoelectric elements. Other methods, such as a patented eddy current measurement for torque determination, are also available.
Feed Force/Thrust Force

The feed force (Z-direction) is considered to also reflect the tool wear as the force required to feed a worn tool are expected to be higher than for a new tool. Some literature states that neither spindle torque nor thrust force gives a consistent change related to tool wear [5] while others state that the thrust force has been considered a more reliable parameter compared to spindle torque [4]. The direct feed force is often measured with the same equipment as the torque measurement and hence also mounted between the machine spindle and the drill holder. The feed force can also be measured by a dynamometer mounted between the work piece and the machine table [3].

Drift Force

The drift force is the lateral force acting between the drill and the work piece. The drift force have been found to give a usable indication of the tool wear, this is believed to be related to a phenomenon where the drill lips are worn in an alternating manner, one lip is worn first and then the other, creating a lateral force [4]. The direct drift force is often measured with the same equipment as the torque measurement and hence also mounted between the machine spindle and the drill holder. As the equipment is constantly rotating the measured force have to be adjusted for the position of the spindle to achieve the force in desired direction. The drift force can also be measured by a dynamometer mounted between the work piece and the machine table, in this case the force is measured in the desired direction directly.

2.2.2 Sound and Vibrations

Sound and Vibrations are always present in machining operations. The characteristics of the vibrations can sometimes be used to determine the tool condition and cutting process in an indirect manner. The vibrations created from drilling usually originate from the dynamics in the cutting zone. Below the different categories of vibrations that have been used in research related to indirect tool wear measurements are described [4].

Structural Vibrations

Structural vibrations describe a mechanical phenomenon where a material oscillates around a theoretical fixed point. Normal frequency ranges for measurement of such vibrations are 1 Hz-20 kHz. Sensors based on piezoelectric elements are commonly used to measure these vibrations. Vibrations are usually measured as velocity (m/s) or acceleration (m/s²) that together with the time series will give potential to generate a frequency spectrum.

Ultrasonic Vibrations and Acoustic Emissions are particular forms of structural vibrations; these are however often considered separately due to their higher frequencies as described below.

Airborne Vibrations (Sound)

Airborne Vibrations, or sound, is a vibration that is transmitted through air. These vibrations are considered hearable by the human ear in the 20 Hz-20 kHz range. Below this range the vibrations are rather felt than heard. Airborne vibrations are commonly measured with microphones.
Ultrasonic Vibrations
Ultrasonic vibrations commonly describe the structural vibrations that occur in the frequency range of 20 kHz-80 kHz [4].

Acoustic Emissions
Acoustic Emissions commonly describe the structural vibrations that occur in the frequency range of 80 kHz and up to 1MHz [6].

2.2.3 Electrical Current
The cutting and feeding force can be indirectly estimated by measurement of electrical current to the spindle- and feed drive motors.

Spindle Motor Current
The spindle motor current can give an indication of both the static and dynamic cutting force. Current can be monitored using clamp meters mounted around the electrical wires for measurement of the generated magnetic field [7]. It is a simple way to estimate the cutting force compared to direct torque measurement but as the sensing unit is not directly in contact with the cutting element this method is less sensitive.

Feed Drive Current
The feed drive motor current might give an indication of the thrust force during drilling as increased electrical power consumption indicates an increased feed force of the drill [4]. Measurement of the feed drive motor current might be both more complex and less sensitive compared to direct measurement as a stepwise movement generates an uneven current consumption that reduces the possibility to analyse the static and dynamic forces in a straightforward way.

2.2.4 Velocity
Cutting Speed
The cutting speed, extracted from the spindle speed, could be utilised as an indicator of the tool degradation especially when dynamics in the revolution speed are analysed as differences in cutting torque could be picked up as changes in the spindle speed.

2.2.5 Displacement
Feed rate
The feed rate has been subject to measurements and analysis in many researches related to tool degradation. It is stated that none have underlined a relation between the feed rate and the level of tool wear [4]. This could be explained as the feed force available is sufficient to maintain a constant feed rate independent of the level of tool wear.

As described in this section, several parameters are available for indirect measurement of tool wear. The CNC-machine built-in sensors have been investigated in the further experimental setup in this work with support from externally mounted force sensors.
3 Method

This thesis work investigates alternative ways to detect drilling tool degradation by using the internal X-, Y- and Z-position sensors of a machine tool. The machine used for the task is a DECKEL MAHO DMC 160 FD duoBLOCK® located at University West’s facilities at PTC, Trollhättan, Sweden.

Prior to the experiments, one set of data collected with the above mentioned machine were roughly analysed to gain understanding in the static and dynamic behaviour of the drilling operation. After this initial analysis the project time frame allowed for one additional set of data collection with one drill, the entire data analysis handled in the thesis is based on these two experimental setups.

The experimental setup where a HSS-drill of 8 mm diameter is operated until failure for acquiring a set of data intended for further analyses. Two different cutting speeds were used, first 35 m/min, or 1393 rpm, which is the highest recommended cutting speed for a HSS drill cutting in mild steel [8], second 70 m/min, or 2786 rpm, which is double of the highest recommended cutting speed. The intention with the increased cutting speed was to wear out the drill in a representative way with reduced machine time and material consumption. The signals are collected with data acquisition system from National Instruments and a MATLAB-based logging system with a logging frequency of 15 kHz.

3.1 Signal analysis

This section presents the different signal analysis methods that are planned for investigation with potential for use in indirect tool wear detection. The methods are selected considering both established methods used in tool wear monitoring as well as some novel theories that are used in other machinery dynamics applications.

3.1.1 Time domain signal features

Analyses in the time domain consists of finding different characteristics of a signal along a time-axis. There are several signal features as described below:

- **Peak-to-peak**

  A block wise peak to peak analysis gives the experienced range during the block of interest, see example in Figure 5 and Figure 6. This method can be a suitable way to pick up changes in the dynamic behaviour over time e.g. increasing run-out during the engagement phase with drill degradation. Other usable areas can be to pick up dynamics in the cutting force by analysing the peak-to-peak values of the spindle torque.

![Figure 5 – Example of block-wise division of a time signal.](image_url)
Amplitude (+/-)
Block wise determination of the maximum and minimum amplitudes are similar to the range analysis. The amplitude analysis replies however two values in form of the positive and negative peaks relative to the average value. This method can be useful when expecting sudden deviations in only one direction e.g. if sudden increase in spindle torque are more likely than a sudden decrease if the material drilled contains particles with higher hardness but none are expected with lower hardness.

XY-scatter
This method is based on combining two signals to form a graphical or mathematical relation between the two inputs. It can be useful to create an orbit plot based on the X- and Y-position or to review a relation between torque and thrust or feed rate and thrust force.

Root Mean Square (RMS)
RMS, also denoted quadratic mean, is calculating the average value of the signal in a block with the exponent 2. The exponent makes this method suitable when handling signals that are fluctuating around a value close to zero as both positive and negative values will be accumulated in the formula:

$$x_{RMS} = \sqrt{\frac{1}{n} (x_1^2 + x_2^2 + \cdots + x_n^2)}$$

The RMS determination is closely linked to the average when handling signals at a noticeable nominal level.

3.1.2 Frequency domain analysis

Analysis in the frequency domain is commonly used for rotating machinery as the rotating motion usually leads to a repeated pattern in some of the signals. The Fourier Transform is an established transform to obtain the frequency content over a specified period of time, see example in Figure 7. The function decomposes the time signal into frequencies with corresponding amplitudes and can reveal useful information both in form of a broad band (random dynamics) or narrow band (strictly repeated dynamics) characteristics. Characteristics below are the most important frequency domain features obtainable from Fourier Transform:

Peak frequency
The method of finding the peak frequency might give valuable information from the amplitude of the dominating frequency. Usually the dominating frequencies in a rotating machine are related to the main rotational speed (1st order) and multiples or factors of this. A clear peak in a frequency spectrum usually indicates a
signal of a repeated pattern that is mechanically (or electrically) connected to the system.

- **Specific frequency range amplitude**
  This method is suitable if special interest in a specific frequency exists. It might be that worn tools have shown to give increased amplitudes in a specific frequency range. Each block of data is analysed as an FFT and the highest amplitude found in a frequency range is selected to represent the block.

- **Waterfall diagram**
  FFT’s can be presented over time as waterfall diagrams. The waterfall diagram is a three-axis graphical presentation where the X-axis represents the frequency, the Y-axis represents the time and the Z-axis represents the amplitude. Waterfall diagrams are useful when analysing trends over time and allow to visualise the development of the frequency/amplitude characteristics.

- **Order tracking**
  Order tracking is a method where the frequencies found are put in relation to the rotational speed of the machine. This might give benefits by increased flexibility with regards to cutting speed as the rotational order can be used instead of a fixed frequency.

![Amplitude Spectrum](image)

Figure 7 – Example of amplitude spectrum spectra showing two distinct vibration modes.
4 Experimental work

The project work is divided into two parts where two different sets of data were analysed. The first set of data were used to familiarise with the signals collected and to gain a general understanding in the different phases of drilling a hole and the different behaviours observed from different sensors. The observations and knowledge gained from this data-set are presented in section 4.1.

The second set of data was collected during an experiment as part of this thesis work and presented in section 4.2. The test setup was defined based on the findings from the first set of data. A description of this setup is found in chapter 3.

4.1 Phase 1 – Pre study of existing data set

During an experimental test carried out related to the potential use of a deburring tool in CNC applications a significant amount of data were gained. This data contained high resolution recording of drilling with different levels of tool wear and were found suitable to use as a pre-study of how the recorded signals collected from the machine could be used to represent the tool wear. The test had been conducted by logging data from drilling operation with tools of different level of wear. The different wear levels were achieved by artificially generated flank wear by grinding.

Data from holes drilled with two different wear levels, “new” and “high wear”, were roughly analysed to give the author a first insight in what signals can be expected from a drilling sequence and the behaviour of these.

Some significant differences between the new and the work tool were found as expected, these are presented in more detail in section 5.1. The review of these data raised three main questions that eventually would found the basis for a second experimental setup. These three questions are summarised below:

- The amount of chips being possibly tangled around the drill is not known from the test. The results could therefore not be fully interpreted if the observed changes in behaviour were related to actual tool wear or the fact that the drill was unbalanced due to chips tangling.
- The artificial tool wear created by grinding could indeed be a representative way to simulate tool wear. It is not known where these wear levels would occur along the time axis of a real case tool wear test. As some analytic theories are based on the gradient changes over time [1, 9-11], the evolution over time has to be considered as valuable information.
- The drill entrance phase was found to be of similar characteristic for both the cases of new and worn tool. This was explained by the artificially created tool wear where the drill tip was kept intact while the flanks were grinded. The effect of the tip condition was considered to potentially be of interest, hence a different approach of applying drill wear was proposed and used in experimental Phase 2.
4.2 Phase 2 – Experimental setup and analysis of data set

From the initial observations from Phase 1, an experimental setup was defined intended to generate valuable data for further analyses aiming at finding suitable methods for determining tool degradation by use of the machine internal sensors. The basic idea of the setup is to execute a drilling operation where 36 holes are drilled in a steel disc with 21.5 mm thickness. The cutting parameters used are according to the maximum recommended settings [8]. Upon completion of this operation the drill was cleaned from any chips tangled around the drill and the 37th hole was drilled with the same parameters as reference.

Figure 8– Schematic view of drilling experiments.
Table 1 – Cutting parameters used in experiment.

<table>
<thead>
<tr>
<th></th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill type</td>
<td>HSS</td>
<td>-</td>
</tr>
<tr>
<td>Number of flutes</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Diameter</td>
<td>8</td>
<td>mm</td>
</tr>
<tr>
<td>Plate thickness</td>
<td>21.5</td>
<td>mm</td>
</tr>
<tr>
<td>Spindle speed</td>
<td>1393</td>
<td>2785</td>
</tr>
<tr>
<td>Cutting speed</td>
<td>35.0</td>
<td>70.0</td>
</tr>
<tr>
<td>Feed/flute</td>
<td>0.1</td>
<td>0.05</td>
</tr>
<tr>
<td>Feed/rev</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Time per hole</td>
<td>0.077</td>
<td>0.077</td>
</tr>
<tr>
<td>Time per hole</td>
<td>4.63</td>
<td>4.63</td>
</tr>
<tr>
<td>Total cutting distance per hole</td>
<td>2.70</td>
<td>5.40</td>
</tr>
<tr>
<td>No. Of holes drilled</td>
<td>37</td>
<td>12</td>
</tr>
<tr>
<td>Total accumulated time (min)</td>
<td>2.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Total accumulated time (s)</td>
<td>171.3</td>
<td>55.6</td>
</tr>
<tr>
<td>Total accumulated distance</td>
<td>100.0</td>
<td>64.8</td>
</tr>
</tbody>
</table>

Upon completion of the operation with normal cutting parameters the cutting speed was doubled and the feed rate halved, see. The intention was to generate a rapid tool wear and produce time stamped data for evaluation of the evolution in signal response that might distorted from the actual tool wear. The hole-pattern is described in Figure 8 together with some additional tests related to other projects carried out in the same experimental session. All holes were drilled with external cooling, see Figure 9.
5 Results and discussion

The data used and collected are analysed according to the proposed methods described in chapter 3, the most fruitful findings are taken into the report while most of the tried methods that where unsuccessful are excluded.

This chapter presents the observations and correlations found from the two different sets of data described in chapter 4.

5.1 Results from experiment with artificially worn tool

The two holes, new and worn tool, analysed from the existing set of data indicates some similarities and some differences that might be related to the level of tool wear. One of the commonly used methods for indirect determination of tool wear is to correlate the cutting torque and the feeding force. In the studied examples seen in Figure 10 the cutting force is represented with the spindle torque. In the graphs each measured value of the two parameters is presented in an XY-scatter where the different dynamics and ranges of required forces are clearly deviating between the use of a new and a worn drill. These signals are collected by means of external sensors and as the intention with the work was to investigate the possibilities of using the machine internal sensors, these data are considered as reference values when analysing the machine internal signals. Figure 11 shows the oscillating XY-forces from the same measured operation, differences are seen and it is assumed that a correlation between the tool wear level and measured X/Y-forces exists. Figure 12 shows the oscillating XY-displacement from the same cutting operations. These signals are collected from the machine internal sensors and are the first indication that the presence of tool wear might be picked-up with these sensors as the characteristics differ between different wear levels. Figure 13 shows similarities in the entry phase with new and artificially worn tool; this is most likely explained by the fact that the tool tip is left unaffected when the drill were grinded, the relevance of this is unknown and further investigated in section 5.2.
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Detection of tool wear in drilling based on axis position signals - Results and discussion

Figure 10 – Graphs showing the different torque/thrust characteristics for new and worn drill.

Figure 11 – Graphs showing the oscillating force characteristics for new and worn drill.

Figure 12 – Graphs showing the oscillating displacement characteristics for new and worn drill.
Figure 13 – Spindle power vs. Thrust force for new and worn drill. Similar behaviour is marked with green oval.

The first steps of analysing the data available from earlier tests point to a possibility to use the machine internal sensors as an indirect measure of the tool wear. The displacement amplitude in the Y-direction is found to increase from ~0.5 µm with a new drill to ~5 µm with a worn drill. An increase of a factor ten is considerable when comparing relative changes over time and might be directly linked to the increased, and potentially fluctuating, cutting forces that are expected when a tool is worn. However, it cannot be ruled out that the fluctuation in work piece position originates from unbalance in the rotating machine caused by chips tangled around the drill. Information of the chip tangling behaviour was not available from the test and a new test was therefore planned where this theory could be confirmed or ruled out.

As reference for different potential analysis methods Figure 14 shows the peak-to-peak values for the X- and Y-position sensor when analysed in steps of 0.1 seconds, new and worn drill are displayed after each other in the same graph. As this figure depicts, the Y-displacement is showing more significant change at different wear levels.
5.2 Results from experiment with normal cutting speed

The first set of the experimental setup for machining operation were conducted with a normal drilling speed and 36 holes were drilled in a continuous operation. Upon completion of this series the drill was cleaned from severe chip tangling and thereafter it was used to drill one more hole as reference. From this set of data two major findings were underlined. The torque-thrust curves seen in experience an offset of ~30 Nm between the first and last hole in the series of 36 holes, upon cleaning of the drill the hole 37 again show a similar level as the first hole. This indicates that the
chips tangled around the drill have an impact in the signals received from the external force sensors.

The overall movement patterns for hole 1 and hole 36 appear similar while for hole 37, drilled in the centre, the Y-amplitude is noticeably higher and the signal has an offset of $\sim$10 $\mu$m. The offset might be explained by the sensor acquisition that sometimes can experience trouble picking up rapid movements between points, this is worth knowing but do not affect the possibility to use the signal as only the dynamics are of interest. The higher amplitude in Y-axis might be explained by the design of the machine table, different positions on the table might be sensitive to different loads in different directions due to the non-homogenous stiffness around the geometry. A waterfall diagram, presented in Figure 18, indicates that the second order ($\sim$46 Hz) is dominating. The fact that the hole 37 experience an unexpected higher amplitude in Y-direction might be explained by the structure being more easily excited due to closer operation to a natural harmonic resonance at this position. It is worth noting the differences in response at the different positions as this might affect the requirement of an algorithm for indirect tool wear determination that is generalised for a range of drilling operations.

Figure 19 is showing the RMS values for the Y-position sensor during drilling of hole 1, 36 and 37. It is seen that the displacement dynamics are higher during drilling of hole 37 even if the cutting force is lower here compared to the hole 36 where chips were tangled around the drill, this is an indication that use of the position sensor might introduce uncertainties that have to be managed.

<table>
<thead>
<tr>
<th>Hole 1</th>
<th>Hole 36</th>
<th>Hole 37</th>
</tr>
</thead>
</table>

**Figure 16 – Torque-Thrust curve from hole 1, 36 and 37 before which drill is cleaned**

**Figure 17 – XY-movement from hole 1, hole 36 and hole 37.**
Figure 18 – Waterfall graph of Y-position sensor where hole 1, 36 and 37 are displayed after each other along the time-axis. See Figure 19 for colour reference.

Figure 19 – RMS value of Y-position sensor for hole 1, 36 and 37.
5.3 Results from experiment with increased cutting speed

As described in section 0, the first 37 holes drilled accumulated only ~4% of the total tool damage from the experimental setup. It can therefore be assumed that the data analysed from these holes would give similar results if the drill were cleaned prior to each hole and the position on the tool table were the same for all holes. Still valuable information of two potential errors from chip tangling and different location of the work table was gathered.

The second test was conducted with the same drill but with the double cutting speed for a rapid evolution of the tool wear. In Figure 20, Figure 21 and Figure 22 the development along the test are represented graphically from hole 1, 8 and 11. The drill ruptured during drilling of hole 12. An increase of all parameters is seen, except for dynamic displacement in X-direction where the amplitude is visibly similar for all holes. This initial analysis in time domain indicates a correlation to the tool wear level between the external sensor information in form of torque, thrust, XY-force and the internal sensor information from the Y-position. To gain a better knowledge in the dynamics during the drilling operation a frequency analysis was carried out and presented as waterfall diagrams in Figure 23. It is seen that in addition to the increase in 1\textsuperscript{st} and 2\textsuperscript{nd} order vibration amplitudes along the tool degradation time, several higher orders experience increase in amplitudes. An area of interest is the range 300-500 Hz where clear signs of amplitude increase are observed along the time of drill degradation. This range is presented isolated in Figure 24 and further in Figure 32 in appendix 1.A.

![Figure 20 - Torque-Thrust curve from hole 1, hole 8 and 11.](image)

![Figure 21 – XY-movement from hole 1, hole 8 and hole 11.](image)
The narrow band single peaks seen at ~360 and ~420 Hz seen in Figure 23 are related to the spindle speed as the 8th and 9th order respectively. So far differences in the machining dynamics have been observed by comparing plots. To further quantify the readings two methods were found successful, single peak and RMS as presented in Figure 25 and Figure 26.

Figure 22 – XY-force from hole 1, hole 8 and hole 11.

Figure 23 – Waterfall diagram over the Y-position sensor during drilling of the 12 holes, 30-800Hz is displayed to exclude low frequency disturbance from different nominal levels.
The Y-axis position signals that are analysed as frequency spectra in blocks of 1 second can be quantified by determination of the highest peak found in the range or by summation of the entire RMS-response in the range 300-500 Hz as seen in Figure 25. These two methods both indicate an escalating development along the drill time used, the peak value indicates a linear development while the RMS value indicates an exponential development. Both of these methods indicate possibilities to be useful for indirect measurement of tool wear evolution and can potentially be implemented with a threshold value for automatic determination [9]. As this method seems fruitful for the specific set-up it was considered that a different setup could give response in a different range, hence the same data is analysed with a widened range of frequencies, 200-800 Hz, in Figure 26 which also gives an indication of correlation between tool degradation developments in the much wider range. It shall be noted that the increase in reference values starts at hole No.6. The MATLAB code for the method is presented in appendix 1.A.

Figure 24 – Waterfall diagram of the isolated range 300-500 Hz showing the time evolution of the 8th and 9th order vibration.
Several attempts were made to find suitable methods from the collected data sets with possibility of easy implementation in real time. One of these methods, peak-to-peak in time domain, is presented to underline some of the drawbacks found. Figure 27 shows the results from a block wise peak-to-peak evaluation from the X- and Y-position sensors. No clear trend is found, the peak in the end of the series is generated from the drill rupture and hence at a too late state of the drill degradation. The main problem with this method is that low frequency impacts are included, these low frequency impacts have their origin in the start and stop of the table’s rotating movement between the holes. An algorithm that determines and excludes these impacts in time domain could be developed, e.g. by determination of a slope in the Z-position that indicates tool engagement. Such method is however considered inferior compared to the above described approach in the frequency domain where these impacts are naturally excluded by selection of a suitable frequency range.
The signal from the Z-axis originally was not found suitable for any of the earlier described methods for analysis as the nominal movement of the axis is considerably higher than the dynamic displacement caused by axial vibration from the drilling. However, this kind of signals can be post-processed by excluding the gradient that is representing the tool movement with the function “detrend” in MATLAB. Examples of the different appearance of the raw signal and the processed signal can be seen as Figure 29.
When the feed gradient is excluded the remaining dynamics can be analysed in the same way as described for the Y-axis. The processed data are presented as graphs in Figure 29 and Figure 30 where a sudden appearance of a narrow band peak appears at 465 Hz after ~30 seconds of drilling time. The frequency is related to the spindle speed as the 10th order and appears at a time, during drilling of hole 6, where a loud sound was heard during the test. At this specific time it is previously seen that the other methods indicate the start of a more rapid development of the reference readings for indirect tool wear determination, potentially related to entering the wear acceleration phase. As the discovered dynamics appears suddenly during drilling of hole 6 it is assumed that the tool experienced a sudden damage, potentially chipping or fracture at one of the lips. The neighbouring holes were examined but no differences in surface appearance were observed with the naked eye. This might indicate that the appearance of this 10th order dynamics could be used as an early indicator of tool damage.

![Waterfall diagram over detrended Z-amplitude for 12 holes.](image)

**Figure 29** – Waterfall diagram over detrended Z-amplitude for 12 holes.

![Z-Peak amplitude in range 100-800 Hz (left) and RMS value in the same range (right).](image)

**Figure 30** – Z-Peak amplitude in range 100-800 Hz (left) and RMS value in the same range (right).
5.4 Taylor’s Equation for Tool Life Expectancy

The collected data from the experimental setup in Phase 2 generated sufficient data for use in the well-known Taylor’s equation for tool life expectancy, \( V_c T^n = C \). The equation is commonly used to extrapolate experimental tool wear data within a specific tool/work piece configuration.

As two different cutting speeds are used for a different amount of total accumulated cutting time an iterative approach was used to combine the accumulated damage from the two different cutting speeds resulting in an estimated factor \( C \) valid for both cases. The parameters used are shown in Table 2 where \( C \) is calculated based on the accumulated time of damage until rupture and \( n \) is selected to 0.16 for HSS [10]. The relation between increased cutting speed and decreased tool lifetime is visualised in Figure 31. The expected lifetime for the two utilised cutting speeds are marked in the chart and one can see the effect of increased tool damage when the cutting speed is doubled. The result of this estimation gives that the first 37 holes that were drilled with “normal” cutting parameters accumulated 4% damage while the 12 holes drilled at doubled speed contributed with the remaining 96% damage until rupture.

<table>
<thead>
<tr>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting speed (Vc)</td>
<td>35,01</td>
</tr>
<tr>
<td>Constant based on data until rupture (C)</td>
<td>69,6</td>
</tr>
<tr>
<td>Constant (n)</td>
<td>0,16</td>
</tr>
<tr>
<td>Calculated lifetime (T)</td>
<td>73,00</td>
</tr>
<tr>
<td>Accumulated drilling time during test</td>
<td>2,86</td>
</tr>
<tr>
<td>Lifetime consumed</td>
<td>4 %</td>
</tr>
</tbody>
</table>

Table 2 – Basis parameters for Taylor calculation.

Figure 31 – Expected tool lifetime according to Taylor with the two used cutting speeds in the experimental setup marked.
6 Conclusion

In the thesis work it is found that suitable methods for quantifying the tool wear level from indirect measurements via the machine internal sensors exists. Analysis of the signals in the frequency domain are considered superior to analyses in the time domain as table movement and other low frequent disturbances are naturally excluded from the result when utilising a suitable range of frequencies.

Analysis of the table movement has benefits compared to measurements directly at the spindle as potential influence of the drill dynamic movement outside the work piece does not require any attention. It might also be more easily analysed as dynamics in the table are negligible when the tool is not engaged. Direct measurements in the spindle might however require complex algorithms to determine the difference between the tool being engaged or not.

The benefits of analysing in the frequency domain compared to the time domain are for instance the independence from sudden impacts caused by table movements as low frequent responses can be excluded.

The Z-axis position sensor gives, after post processing, clear indications of a sudden change in dynamic behaviour during drilling of hole No.6. It is from this point, and on, the Y-axis analysis start of the tool wear acceleration is indicated. Hence the Z-axis position sensor is considered potential for use in early determination of entering of the wear acceleration phase.

6.1 Future Work and Research

- It is desirable to evaluate how the sensor response is affected by different X/Y-positions. A test where holes are drilled over the entire work area with only X and Y-movements may reveal different behaviour compared to the studied cases where X-Y movement was avoided and new holes were made by indexing the rotary table.

- It is proposed to log data from one specific tool over its utilised lifetime, independent of operation. This could reveal if the proposed methods are suitable also for a non-structured life-cycle.

- It is proposed to log data with defined cutting parameters prior to and after operation to document the deviation in dynamic behaviour after a conservative utilisation.

- The drill used during the main tests experienced several modes of wear and damage, the different damages are expected to generate different unbalance in the forces and hence displacement dynamics. It is believed that further studies of the radial and axial dynamics from different kind of tool wear might reveal a correlation that can further refine the proposed method to also determine the kind of damage experienced.
6.2 **Critical Discussion**

It is observed that the equipment used for force measurements directly on the spindle will change the mass-elastic system. This might affect the dynamic behaviour, both positive and negative depending on the spindle speed, with regards to harmonic resonances as the stiffness is changed. This might affect the outcome if a similar test is carried out without this equipment. The excitation frequencies are not expected to change, but the displacement response might. The tool stick out is also believed to affect the response as the stiffness is altered with alternating length.

6.3 **Generalisation of the result**

Analyses of frequency response in the range of 8th-10th order of rotation have not been found commonly used in the reviewed articles. It is believed that the proposed method can be implemented also for milling after some tuning of the method. Turning, that usually have lower ratio of rpm to cutting speed, might require a different approach where the cutting speed has to be the basis.
7 References


A. Graphs

Figure 32 – Waterfall plots from Y-displacement with zoomed area of interest.
B. MATLAB code

MATLAB code for peak-search and RMS averaging of a frequency range, **yellow mark-up** indicates name of matrix subject to analysis

```matlab
clearvars TotalBlocks Startpoint Endpoint dim Time T L t Y P1 P2 f range maxvalue FFTSpectra RMSvalue;
close all;
Fs = 15000; %Sampling frequency (Hz)
Step=1; %Block size (s)
TotalBlocks=floor(size(Data12,1)/Fs/Step); %Number of full blocks (n)
Rangestart=300; %Frequency range start (Hz)
Rangestop=500; %Frequency range stop (Hz)

for i=1:TotalBlocks
%FFT
Startpoint=(1)+(((i)-1)*Fs)*Step; %Block starting point
Endpoint=Startpoint+(Step*Fs); %Block stop point
Time(i,:)=i*Step; %Block position (s)
T = 1/Fs; %Sampling period
L = (Step*Fs); %Length of block
t = (0:L-1)*T; %Time vector (s)
Y = fft(Data12(Startpoint:Endpoint,3)); %Block FFT Analysis
P2 = abs(Y/L); %Two-sided spectra
P1 = P2(1:L/2+1); %Single sided spectra
P1(2:end-1) = 2*P1(2:end-1); %Single sided spectra
f = Fs*(0:(L/2))/L; %Frequency vector (Hz)
range=P1(Rangestart:Rangestop); %Range of interest (Hz)
FFTSpectra(i,:)=P1'; %Store block spectra in matrix
maxvalue(i,:)=max(range); %Store peak value for range per block
RMSvalue(i,:)=rms(range); %Store RMS value for range per block
end
figure
plot(Time,maxvalue)
title('Maximum peak in range of 300-500 Hz, Y-movement')
xlabel('Time (s)') % x-axis label
zlabel('Maximum peak amplitude (mm)') % y-axis label
figure
plot(Time,RMSvalue)
title('RMS-value of range 300-500 Hz, Y-movement')
xlabel('Time (s)') % x-axis label
zlabel('Maximum peak amplitude (mm)') % y-axis label
FFTSpectraMin=FFTSpectra(:,1:800);
figure
waterfall(FFTSpectraMin)
title('Waterfall diagram, Y-movement over time for the 12 holes')
xlabel('Frequency (Hz)') % x-axis label
zlabel('Displacement range (mm)') % y-axis label
ylabel('Time (s)') % y-axis label
```