Modeling of Metal Cutting

C. Rademakers

DCT 2007.153

Training Period
Student number: 533922

Coaches: M. Eyian
          H. Onozuka
Supervisors: Prof. H. Nijmeijer
            Prof. Y. Altintas

Technische Universiteit Eindhoven
Department of Mechanical Engineering
Section Dynamics and Control Technology

Eindhoven, October 2007
Summary

This report covers the work done during a three month internship at the Manufacturing Automation Lab at the University of British Columbia. The internship project is part of ongoing research to expand the scope of predictive chatter theories from simple tool geometries and cutting force models to the more realistic cutting force models involved in industrial cutting processes. During the internship an orthogonal cutting force model is made and compared with oscillating cutting tool measurements. To create the orthogonal model first the existing literature is studied on the theory behind cutting mechanics and on current knowledge of chatter prediction models. Afterwards the tools, the lathe and measuring equipment are tested and calibrated to ensure proper measurement data. Next the chip geometry and cutting forces for various cutting conditions are measured. These measurements are implemented in the model. Finally the model is compared with oscillating cutting data. This verifies if the model is usable for further research in chatter prediction and clarifies if parts of the model need improvement.
Table of Contents

Summary 2
List of Symbols 4
Preface 5
1. Introduction 6
   1.1 Metal Cutting 6
   1.2 The Project Goal 7
   1.3 Outline of the report 7
2 Cutting Mechanics 8
   2.1 Chip formation 8
   2.2 Force Analysis 10
   2.3 Initial tests and Model setup 12
3 Chatter 13
   3.1 Machine vibrations 13
   3.2 Self excited vibrations 13
   3.3 Mode Coupling and Regeneration 14
   3.4 Analyzing machine tool chatter 15
4 Experiments 16
   4.1 Setup of the experiments 16
   4.2 Calibration 17
   4.3 Force measurements 19
   4.4 Edge Radius Measurement 21
   4.5 Chip measurements 21
   4.6 Hardness testing 22
   4.7 Analyzing the results of the experiments 23
5 Oscillation tests 28
   5.1 Oscillating cutting model 28
   5.2 Comparing the force model 28
6 Conclusions and Recommendations 30
Literature 31
Appendix A First Test Results 32
Appendix B Dynamometer sensitivity measurements 33
Appendix C Dynamometer calibration 35
Appendix D Error analysis of chip thickness measurements 36
Appendix E Dytran impulse hammer 37
Appendix F Contour Tracer 38
Appendix G Hall Sensor 39
Appendix H Detecting Chatter using CUTpro 40
Appendix I Matlab model 41
## List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f$</td>
<td>[m]</td>
<td>feedrate</td>
</tr>
<tr>
<td>$h_o$</td>
<td>[m]</td>
<td>depth of cut</td>
</tr>
<tr>
<td>$h$</td>
<td>[m]</td>
<td>chip thickness</td>
</tr>
<tr>
<td>$l_c$</td>
<td>[m]</td>
<td>chip length</td>
</tr>
<tr>
<td>$m_c$</td>
<td>[kg]</td>
<td>chip mass</td>
</tr>
<tr>
<td>$r_c$</td>
<td>[-]</td>
<td>compression ratio</td>
</tr>
<tr>
<td>$w$</td>
<td>[m]</td>
<td>width of cut</td>
</tr>
<tr>
<td>$A_s$</td>
<td>[m$^2$]</td>
<td>shear plane surface</td>
</tr>
<tr>
<td>$F_f$</td>
<td>[N]</td>
<td>feed force</td>
</tr>
<tr>
<td>$F_s$</td>
<td>[N]</td>
<td>shear force</td>
</tr>
<tr>
<td>$F_t$</td>
<td>[N]</td>
<td>tangential force</td>
</tr>
<tr>
<td>$K_{fc}$</td>
<td>[N/m$^2$]</td>
<td>feed cutting constant</td>
</tr>
<tr>
<td>$K_{fe}$</td>
<td>[N/m$^2$]</td>
<td>feed edge constant</td>
</tr>
<tr>
<td>$K_{tc}$</td>
<td>[N/m$^2$]</td>
<td>tangential cutting constant</td>
</tr>
<tr>
<td>$K_{te}$</td>
<td>[N/m$^2$]</td>
<td>tangential edge constant</td>
</tr>
<tr>
<td>$N_s$</td>
<td>[N]</td>
<td>shear plane normal force</td>
</tr>
<tr>
<td>$R$</td>
<td>[N]</td>
<td>resulting force</td>
</tr>
<tr>
<td>$V$</td>
<td>[m/s]</td>
<td>cutting speed</td>
</tr>
<tr>
<td>$\alpha_r$</td>
<td>[rad]</td>
<td>rake angle</td>
</tr>
<tr>
<td>$\beta_a$</td>
<td>[rad]</td>
<td>friction angle</td>
</tr>
<tr>
<td>$\rho_c$</td>
<td>[kg/m$^3$]</td>
<td>chip density</td>
</tr>
<tr>
<td>$\tau_s$</td>
<td>[N/m$^2$]</td>
<td>shear stress</td>
</tr>
<tr>
<td>$\phi_c$</td>
<td>[rad]</td>
<td>shear angle</td>
</tr>
</tbody>
</table>
Preface

For almost a decade traveling has been (and still is) my biggest hobby. So when the opportunity to spend several months abroad presented itself in the form of a training period, I seized it with both hands and started planning. The training period is part of the graduate curriculum of the department of Mechanical Engineering at the Technical University of Eindhoven (TU/e) and the faculty stimulates students to go abroad for this period. I’ve had the wish to explore the north-American continent for some time and heard many good stories about Vancouver. So I set my goal for Canada.

Unfortunately there were no initial contacts within Vancouver, so I had to find a position myself. After a month of searching I got in contact with Professor Altintas of the University of British Columbia (UBC), who was willing to accept me as a visiting scholar at the Manufacturing Automation Lab (MAL). The Lab conducts research in the mechanics and dynamics of metal cutting operations, machine design and analysis and machining operation modeling and simulation. For automotive engineering students, machining forms an important part of their study as nearly all parts in modern automobiles are machined in one way or another.

During the 13 weeks in Vancouver I got a glimpse of what makes the city tick. Surrounded by the sea and the mountains, the nature just seems to get into everybody. Despite the vast amounts of rain (the record is 28 days straight) outdoor activities are the most popular pastime besides drinking coffees. Fortunately I share these hobbies with most Vancouverites, so whenever I was not working at the lab I could be found snowboarding on a local mountain, cycling along the waterfront or buying a coffee and a muffin at a coffee bar.

Next to life in the city I also found great satisfaction in my work at the lab. From the beginning I was encouraged to conduct experiments and contribute to M. Eyian and H. Onozuka’s work. The lab has state-of-the-art research tools and machinery and is fully equipped to conduct research in all aspects of machine tools and machining engineering. I’m glad I’ve been able to make a valuable contribution to the lab. After four months I left Vancouver with the feeling, that like all good things, it had ended too soon.

I would like to thank Madhi and Hideaki for all the help and friendliness they offered and their patience in explaining me their work. Also, I would like to thank Professor Y. Altintas for allowing me to be part of his research group and Professor H. Nijmeijer for giving me the opportunity to open a new relation between the University of British Colombia and the Technische Universiteit Eindhoven.
1. Introduction

The research covered in this report is a small contribution to ongoing chatter research. To clarify the importance of chatter research chapter 1 starts with an introduction to metal cutting and its importance (chapter 1.1). Next the goal of the project covered by this report is explained in chapter 1.2. In chapter 1.3 the outline of the rest of the report is given.

1.1 Metal Cutting

Altering the geometry of objects by removing material has been of great importance throughout history. From the first use of tools to highly advanced computer numerically controlled machining. Nowadays practically all material removal is done by machining. The importance of machining in today’s society can easily be seen in the world around us where almost every device consists of one or more machined surfaces or holes. This importance can be emphasized by considering the following: In the United States the annual costs associated with the removal of material is estimated at 10% of the Gross National Product [1]. This Report deals with one of the many forms of material removal operations; the removal of metal by cutting on macro-level: Metal Cutting.

![Diagram of cost reduction and tool life](image)

**Figure 1.1 - Sample from the Sandvik catalogue ‘turning tools’**

The final shapes of most mechanical parts are obtained by machining operations. Bulk deformation processes, such as forging and rolling, and casting processes are mostly followed by a series of metal removing operations in order to achieve parts with desired shapes, dimensions, and surface finish quality [2]. The three most popular forms of machining are turning, milling and boring. Metal cutting machines capable of performing these operations exist in a wide range of sizes, capacities and costs. Every machine however consists of three basic parts: The frame, the work piece and the tool. Machining operations are directly dependent on the dynamic relation between the work piece and cutting tool. Under certain circumstances, vibrations in the motion of the tool against the work piece can result in a self-exciting system, causing the vibrations to increase in amplitude. These large self-induced vibrations are known as ‘chatter’. Chatter
is considered the most problematic and main limiting factor for milling and turning processes. Chatter results in poor surface finish, fatigue, noise and excessive tool wear. This makes chatter research a major topic in mechanical engineering (figure 1.1).

1.2 The Project Goal

The goal of the internship project is to create a model that predicts the cutting forces in an oscillating-tool turning process to better understand process damping. This model can later be used and further expanded during the Ph.D. research of M. Eyian. The ultimate goal of the Ph.D. research is to create a more practical chatter prediction theory involving specific tool geometries, material properties and cutting conditions. To aid the process of creating this new theory, a proper model is needed to predict cutting forces during oscillating cutting conditions. Ultimately this model will predict cutting forces for any given material, tool geometry and cutting condition. However, creating such a model is far too much work to cover in three months. Therefore the goal of this project is to create a cutting force model for Steel 1018 using specific cutting tools.

1.3 Outline of the report

In order to start creating the model, basic knowledge of cutting mechanics and current theories behind chatter prediction is needed. Therefore a literature study is done. Cutting mechanics and chatter theory are summarized in chapter 2 and 3 respectively. The model is based on empirical cutting data. Therefore a lathe is set up for cutting experiments (chapter 4.1) and a dynamometer is calibrated (chapter 4.2). Various properties of the cutting process are measured and evaluated; Cutting forces (chapter 4.3), edge forces (chapter 4.4), chip geometry (chapter 4.5) and material hardness (chapter 4.6). The result of these measurements and the implementation into the model is explained in chapter 4.7. Next the cutting force prediction of the model for oscillating cutting conditions is compared to experimental data to analyze coherence and determine future improvements (chapter 5). The report is finished with an evaluation, conclusions and recommendations (chapter 6).
2 Cutting Mechanics

Metal cutting is an age old technology. Therefore a large amount of literature on metal cutting mechanics exists. This chapter forms a brief summary of the theories used at present. First in chapter 2.1 the formation of the chip is analyzed and the key terms ‘shear angle’ and ‘compression ratio’ are introduced. Chapter 2.2 continues with the cutting forces and cutting pressure. The last chapter, chapter 2.3, bridges the gap between the variables used in the theoretical approach to metal cutting and the practical parameters used in machining.

2.1 Chip formation

The most fundamental and crucial characteristic of metal cutting mechanics lies in the formation of the chip. Despite a misleading title it is not exactly ‘cut’ but ‘sheared’ away from the work material, which forms a clear distinction between cutting metal and cutting other materials (i.e. wood). Figure 2.1 is a photomicrograph snapshot of the chip formation process during metal cutting [1]. It shows a partially formed chip, with the tool approaching the material from the right side and the chip flow in upward direction. When the original chip thickness or feed rate or depth of cut (distance x) is compared with the chip thickness after cutting (line A-B), the deformation can clearly be observed.

![Figure 2.1 - photomicrograph snapshot of cutting process [4]](image)

This deformation is fundamental for the metal cutting process and involves large deformations of material with very large strains and very high strain rates. The produced chip is in contact with the tool face in a highly pressurized zone causing sticking friction which transforms to sliding friction further up on the tool face. A large amount of heat is generated in the cutting zone as a result of plastic work and friction, causing large
temperature rise in the tool and the chip. Strain rate and temperature have opposite effects on the properties of the material. Considering the fact that all of these phenomena occur in a very small region around the tip of the tool, the complexity of the process becomes clear (figure 2.2).

To analyze the deformation it is best to start with an orthogonal (or 2 dimensional) cutting model. In orthogonal cutting the cutting process is uniform along the cutting edge. There is no flow of metal in the direction parallel to this edge (figure 2.3), i.e. the width of the cut (w) does not change. This is known as Stabler’s rule [7].

The first orthogonal model was created in 1937 by Piispanen [3] and is known as the
card model (figure 2.4). Despite the limitations of this model the main concept is still the basis of most new cutting models. The model depicts the material cut as a deck of cards inclined to the cutting direction. Piispanen’s model was later improved by Merchant (1944). Merchant’s model is the basis for this report.

![Piispanen's card model](image)

**Figure 2.4 - Piispanen’s card model [1]**

Merchant assumed the chip to be formed over an infinite thin plane called the shear plane (figure 2.3). The shear plane starts from the cutting edge of the tool and crosses the chip on an angle with the cutting direction: the shear angle ($\phi$). When the chip passes the shear plane it is sheared away from the work piece and increases in thickness. The ratio between the initial depth of cut ($h_0$) or feed rate and the final chip thickness ($h$) is called the compression ratio ($r_c$).

### 2.2 Force Analysis

The forces in the shear plane (the shear force and the normal force) are the main contributors to the total force experienced by the tool. Other contributors are friction on the rake and relief face of the tool and elastic compression of the work piece. The total force is the immediate result of the initial setup parameters (i.e. feed rate ($h_0$), cutting speed ($V$), tool shape, rake angle ($\alpha$) or width of cut ($w$)). Any change in these parameters instantly changes the force balance and dynamics of the system. One important aspect of Merchant’s model is the separation of the resulting force ($R$) from the shearing process into three separate pairs (figure 2.5). Calculations of the forces is normally based on the shear plane orientation set ($F_s$, $N_s$) and recalculated to the tool orientation set ($F_t$, $F_f$ ($F_p$ and $F_q$ in figure 2.5)).
Figure 2.5 - Merchant’s force components in orthogonal cutting [4]

Following Merchant’s model the tangential and feed force \( F_t, F_f \) can be represented as a function of the cutting conditions \((w, h)\), the cutting constants \((K_{tc}, K_{fc})\) and the edge coefficients \((K_{te}, K_{fe})\) [2]. These terms relate to the cutting forces via:

\[
F_t = K_{tc} \cdot wh + K_{te} \cdot w \tag{2.1}
\]

\[
F_f = K_{fc} \cdot wh + K_{fe} \cdot w \tag{2.2}
\]

As mentioned above the forces due to shearing are not the only contributors to the cutting forces. Other sources are friction between the rake face of the tool and the chip, friction between the relief face of the tool and the work piece and elastic deformation between the tool and work piece. These forces are represented in (2.1) and (2.2) by the edge coefficients and can only be determined from specific tool – work piece cutting tests. The cutting constants can be calculated using four parameters, called the process- and material-dependant terms: the rake angle \((\alpha_r)\), the friction angle \((\beta_a)\), the shear stress \((\tau_s)\) and the shear angle \((\phi_c)\). These cutting constants relate the uncut chip surface (width and height) to the cutting forces and are therefore also known as the cutting pressure:

\[
K_{tc}[N/m^2] = \tau_s \frac{\cos(\beta_a - \alpha_r)}{\sin \phi_c \cos(\phi_c + \beta_a - \alpha_r)} \tag{2.3}
\]

\[
K_{fc}[N/m^2] = \tau_s \frac{\sin(\beta_a - \alpha_r)}{\sin \phi_c \cos(\phi_c + \beta_a - \alpha_r)} \tag{2.4}
\]
This means that when the four process- and material dependent terms are determined, the major cutting forces in the process can be calculated directly. Obviously the rake angle can be measured directly from the tool geometry and is often given in the product specifications. The other terms however cannot be measured that easily. Although various models have been suggested to predict the shear angle (Ernst & Merchant, Lee & Shaffer and Dautzenberg [8]) an accurate, analytical prediction remains the subject of continuing research [2].

2.3 Initial tests and Model setup

The main purpose of the model is to predict the cutting forces as accurately as possible for an oscillating tool cutting test. Therefore the model should be able to determine the cutting forces for any given setup condition. Initial tests, performed to become acquainted with the machine, have shown that two process variables had the largest influence on the resulting cutting forces. These two variables are the cutting speed and the feed rate. Unfortunately, as shown in the previous chapter, there is no theoretical relation between these variables and the process- and material-dependent terms, which are required to calculate the cutting forces. To bridge this gap an empirical relation for the shear angle ($\phi_c$), friction angle ($\beta_a$) and shear stress ($\tau_s$) was researched. This empirical relation is based on research done by E. Usui. [9], who worked with an exponential relation between the three variables and the two setup parameters:

$$\phi_c = e^{0.0587V + 1.0398f - 1.2392}$$  \hspace{1cm} (2.5)

$$\tau_s = e^{0.0059V - 0.4246f + 6.3211}$$  \hspace{1cm} (2.6)

$$\beta_a = e^{-0.0006V - 0.6924f - 0.4704}$$  \hspace{1cm} (2.7)

Dr. Usui used Japanese grade steel of unknown hardness and an unknown range of setup conditions. This required a new calculation of the exponential relation between the cutting speed and feed rate and the three variables. The setup and results of these experiments are described in chapter 4.1 to 4.5. The resulting exponential relation is described in chapter 4.6.
3 Chatter

The main topic of this report, the internship and the project; Chatter has been a subject of ongoing research for many years and still is. This chapter gives a summary of what is nowadays considered as the driving mechanics behind chatter. It starts with an explanation of machine vibrations in chapter 3.1, continues with the category of machine vibrations called self-excited vibrations in chapter 3.2 and the two main forms of self-excited vibration: mode-coupling and regeneration in chapter 3.3. The final part, chapter 3.4, gives insight into how machine tool chatter is detected and analyzed.

3.1 Machine vibrations

As mentioned in the introduction of this report the multi-part assembly of metal cutting machines creates a complex dynamic structure, which is subjected to vibrations. These vibrations in turn can lead to degrading accuracy, rough surface finish, excessive tool wear and even damage to the machine tool and part. Furthermore they are the main limiting factor in production rates. Machine vibrations can be divided into three categories: Free, Forced and Self-excited vibrations. Free or transient vibrations originate from singular impulses on the structure (e.g. the initial tool – work piece engagement or shocks entering through the foundation). Forced vibrations are the result of periodic vibrations within the system (e.g. unbalanced rotating masses). Self-excited vibrations are the result of dynamic instabilities and are the least desirable type of vibration because the structure enters an unstable condition. Both free and force vibrations can easily be prevented by using the right combination of damping and balancing. Self-excited vibrations however do not result directly from external forces, but draw energy from the cutting process itself. In other words, disturbances in the cutting process (e.g. a hard spot in the material) are fed back into the system and over time may results in instability, which can grow in amplitude until limited by non-linear effects (i.e. tool – work piece disengagement).

3.2 Self excited vibrations

Self-excited vibrations are commonly referred to as machine tool chatter. While initially thought to be caused by negative damping, chatter was later recognized to be the result of regeneration or mode coupling. Both of which occur because of the basic interaction between the cutting process and the machine tool structure. The force generated between the tool and work piece can be represented as a single vector (R), due to the relatively small area of contact. This force is mainly dependent on the cutting speed and feed rate, as shown in chapter 2.3. The structure reacts elastically on this force which in turn alters the tool – work piece engagement and configuration, which alters the feed rate and cutting speed, which changes the cutting force. The result is a closed-loop feedback system between the machine, tool and work piece (figure 3.1).
3.3 Mode Coupling and Regeneration

In cutting dynamics two modes of self-excited instability are distinguished: mode coupling and regenerative chatter. Mode coupling occurs when the motion of the tool acts in the vicinity of closely coupled modes of vibration. The characteristics of the structure can cause the tool to follow an elliptical path relative to the work piece (figure 3.2). In the lower part of the elliptical path the increased feed rate results in an increase of the force $R$, thereby increasing the amount of work put into the system. Since the lower feed rate in the upper part results in less work taken out of the system, the system supplies its own energy and thereby has a tendency to become unstable.

When a disturbance results in a wavy structure and this wavy structure is increased in successive passes, the instability is called regenerative instability (figure 3.3). The wavy surface from the previous cut result in variations in feed rate, rake angle and cutting velocity, which results in variations in shear angle and cutting forces, which in turn result in machine vibrations. When the dynamic cutting force is out of phase with the instantaneous relative motion between the tool and the work piece, this leads to the development of self-excited vibrations. The level of increase of vibration depends on the phase shift between successive waves.
3.4 Analyzing machine tool chatter

The stability limit of the tool-machine combination (tool: Sandvik Coromat: BG-154-91-3-H13A, machine: Hardinge Superslant Lathe) is tested for various cutting speeds and feed rates. The stability limit of the tool is reached when chatter occurs. Chatter occurrence is audible and can be detected using a microphone. This is a common method for detecting chatter. The program CUTpro however, has a more thorough method for analyzing chatter (Appendix H). The results are plotted for various spindle speed and feed rates to produce a stability chart (figure 3.4).

Stability charts are typically used to analyze the stability of a machine tool. One of the main goals of chatter research is to accurately predict a stability chart for any given material, tool and cutting condition combination.
4 Experiments

The current knowledge of metal cutting mechanics leaves a gap in determining cutting forces from machine setup parameters and material properties. The only way to determine this unknown relation is to include empirical data into the model. Therefore several experiments are performed and described in this chapter. First the setup of the experiments is explained in chapter 4.1 and the calibration of the dynamometer and the lathe described in chapter 4.2. Next the measurements from the experiments are explained. During the experiments cutting forces, the edge radius of the tool, chip geometries and material hardness are measured. The results are written in chapter 4.3 to 4.6 respectively. In the final part of this chapter, chapter 4.7, the results of the experiments are evaluated.

4.1 Setup of the experiments

To create the model, the relation between the setup parameters \((f, V)\) and the process variables \((\beta_a, \tau_s, \phi_c)\) have to be determined, as shown in chapter 2.3. To do so the cutting forces \((F_f, F_t)\) and the chip compression ratio \((r_c)\) are measured for a wide range of feed rates and cutting speeds. The forces and compression ratio can be recalculated into the process variables using:

\[
\beta_a = \alpha_r + \tan^{-1}\left(\frac{F_f}{F_t}\right) \quad \text{(4.1)}
\]

\[
\tau_s = \frac{F_s}{A_s} = \frac{F_t \cos \phi_c - F_f \sin \phi_c}{bh} \quad \text{(4.2)}
\]

\[
\phi_c = \tan^{-1}\left(\frac{r_c \cos \alpha_r}{1-r_c \sin \alpha_r}\right) \quad \text{(4.3)}
\]

After calibrating the machine cutting tests are performed. During these tests the cutting forces are measured using a dynamometer. The geometry of the chips is measured to determine the compression ratio and the results are analyzed and compared with the existing empirical data from Usui [9].
Cutting forces are measured using a piezoelectric dynamometer. The use of this is highly preferable over other methods such as hydraulic, pneumatic or strain gage instruments. Piezoelectric dynamometers show high stiffness, broad frequency response and high thermal stability. One disadvantage however is slight static crosstalk between measurements in different directions [7]. To ensure the realistic cutting conditions (one of the major goals) an everyday tool is used: A tool insert holder (Sandvik Coromat: L154.91-2020-3) and carbide tungsten inserts (Sandvik Coromat: BG-154-91-3-H13A). During the first measurements a piezo actuated tool servo is mounted between the turret and the dynamometer. This is done to keep the setup as similar as possible between the oscillating and static cutting tests. The tool servo is designed by M. Eyain and H. Onozuka to perform oscillating cutting tests. The first result however were unsatisfying (appendix A). After testing the sensitivity of the oscillating cutting tool setup it showed there is not enough stiffness to guarantee proper force measurement data (see Appendix B). Next to the expected low vibration sensitivity (at ± 600 Hz.) the setup had an undesirably high sensitivity at 1500 and 2100 Hz. This is caused by the zero charge on the piezo actuator. Unfortunately this can not be changed therefore the oscillating cutting tool is replaced with a stiffer dynamometer.

4.2 Calibration

The dynamometer is dynamically and statically calibrated. Static calibration consisted of applying various loads to the dynamometer in all three directions and measuring the output signal. The dynamic calibration is performed using a dytran impulse hammer (appendix E) and the MAL software program ‘Cutpro’ to analyze and compare the input / output spectrum (appendix B). This resulted in the relations between the forces that are applied ($F_{\text{work}}$) and the force values returned by the dynamometer ($F_{\text{dyno}}$) (table 4.1) which are used to correct the force measurements (appendix C).
During the calibration measurements the dynamometer also shows considerable drift in the output. This drift is visible as an offset between the ‘zero-force’ level of the dynamometer before and after the cut. These levels can easily be measured in Cutpro. The difference between these levels is used to correct the force measurements.

Another important parameter during the experiments is the accuracy of the rotational speed of the Hardinge Superslant lathe. During regenerative chatter, where several ‘feedrate’ waves are created in one revolution, a small phase lag creates large differences in cutting forces and stability. Therefore it is very important for the work piece to rotate at precisely the entered value. To test this, a hall-sensor (Appendix G) is connected to the turret and a small metal plate attached to the chuck. The signal of the hall sensor was collected using the MALDaq and CUTPro (figure 4.2).

<table>
<thead>
<tr>
<th>$F_{\text{dyno}}$</th>
<th>$F_{\text{work}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.01</td>
<td>-0.01</td>
</tr>
<tr>
<td>-0.05</td>
<td>1.51</td>
</tr>
<tr>
<td>-0.01</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>1.01</td>
</tr>
</tbody>
</table>

*table 4.1*

*figure 4.2 - spindle frequency calibration*
When the signal from the hall sensor is converted to the corresponding rotational frequency the following errors are found (Table 4.2)

<table>
<thead>
<tr>
<th>spindle frequency [rpm]</th>
<th>100</th>
<th>250</th>
<th>500</th>
<th>750</th>
<th>1000</th>
<th>1500</th>
<th>2000</th>
<th>2500</th>
<th>3000</th>
<th>4000</th>
</tr>
</thead>
<tbody>
<tr>
<td>error [%]</td>
<td>7.93</td>
<td>15.61</td>
<td>4.62</td>
<td>2.04</td>
<td>1.87</td>
<td>1.78</td>
<td>1.35</td>
<td>1.27</td>
<td>1.52</td>
<td>2.04</td>
</tr>
</tbody>
</table>

It is clear that especially in the low turning frequencies the lathe shows considerable error. For example a 4.62 % error at 500 [rpm] using 10 ‘feedrate’ waves per revolution means 166 degrees phase lag instead of 0.

4.3 Force measurements

The signals from the dynamometer are captured using the MALDaq (data acquisition card) and processed using CutPro. A sample of such a signal can be seen in figure 4.3.

The raw cutting force data is the average signal strength over the stable period in the cutting process (for example: in figure 4.3 between 6.2 and 8.8 sec). The average signal strength is calculated in CutPro using a Fast Fourier Transformation of the stable period. The raw cutting force is thereafter corrected using the transfer function (see chapter 3.2.) and the drift correction. The drift is measured by determining the difference between the zero force signal before and after the cut (for example: in figure 4.3 at 4.2 and 10 sec). The radial and tangential cutting forces are measured for four cutting speeds: 50, 75, 100 and 150 [m/min]. When the tangential cutting force is plotted against the feed rate (figure 4.4) the linear relation following (2.1) can be seen.
From these results the edge coefficients are determined. Since the edge coefficients relate to the forces that are independent of the feed rate, these coefficients can be found by looking at the zero feed rate value of the measured cutting force. In later calculations the forces are corrected for this. The radial cutting forces (figure 4.5) show irregularities in the linear relation. This is believed to be due to a relatively large edge radius.
4.4 Edge Radius Measurement

In Merchant’s model the edge radius (the radius between the rake and relief face) is assumed dead sharp. In practice however this is not the case. To get an idea of the edge radius dimensions a contour tracer was used to determine the radius (appendix F). figure 4.6 shows the results of the contour measurements. The average edge radius was found to be 33 [mm]. The diamond stylus has a radius of 5 [mm], which leaves an average edge radius of 28 [mm].

![figure 4.6 - measurement results contour tracer](image)

These results show the edge radius to be of significant size compared to the feed rate, therefore the lower feed rate measurements were omitted in later calculations.

4.5 Chip measurements

The compression ratio of the chips during the cutting process determines the shear angle (3.3). Measuring the compression ratio is done by comparing the feed rate (the uncut chip thickness) with the cut chip thickness. The thickness of the produced chips can be measured by using the specific density:

\[
h_c = \frac{m_c}{r_c l_w}
\]

The mass of the chips is measured using a high sensitivity scale. The length of curled-up chips is calculated by measuring the diameter of the curl, the length of the curl and the amount of windings (figure 4.7). Using the density of the work piece material given by the manufacturer, the thickness is calculated. Using this method shows less scatter than direct measurements and is regarded as more reliable than micrometer or optical measurements [7]. Error analysis shows a chip sample from a cutting test has to be of at least 10 [mm] in total length and 0.01 [g] in total weight.
4.6 Hardness testing

During the cutting experiments the question is raised whether if the hardness of the work piece material is changed during the forming process or during the cutting process due to cold work. To be sure this has no significant influence on the test results a hardness test of several samples of the work piece material is performed. Slices were cut from the steel 1018 and steel 1045 rods and tested on various places (figure 4.8). The hardness tests show no significant change in hardness.
4.7 Analyzing the results of the experiments

First the shear angle, shear stress and friction angle are calculated using (3.1), (3.2) and (3.3) (appendix G). The effects of the conclusion drawn following the edge radius measurement results (chapter 3.3) can be seen in figure 4.9. At low feed rates the edge radius is too large compared to the uncut chip thickness a significantly influences the measurement results. Only when the ratio between the edge radius and the feed rate reaches 1:3 (at 0.08 [mm/rev]) the results show a clear relation. Therefore the results below 0.08 [mm/rev] are omitted in determining the exponential relation.

The calculations of the shear stress (figure 4.10) shows similar results. In contrast to the shear angle however the accuracy of the shear stress is also dependent on the accuracy of the force measurements (3.2). Since these measurements are not influenced by the edge radius, they have a higher accuracy at low feed rates and the graph of the shear stress shows a clearer relation with the feed rate.

![figure 4.9 - shear angle measurement result](image_url)

![figure 4.10 - shear stress measurement result](image_url)
The calculation of the friction angle is only dependent on the measured forces (3.1) and is therefore a good indication of the accuracy of these measurements. Figure 4.11 shows these measurements are accurate from a feed rate of approximately 0.02 [mm/rev], but since the influence of the edge radius already caused the measurements below the feed rate of 0.08 [mm/rev] to be omitted, this is of no further consequence.

The exponential relation between the process parameters and the cutting speed and feed rate was empirically determined to be:

\[
\varphi_c = e^{0.2198V + 1.6626 f - 1.3085} \quad (4.5)
\]

\[
\tau_s = e^{0.0013V - 0.3211 f + 6.5659} \quad (4.6)
\]

\[
\beta_a = e^{-0.0546V - 0.8856 f - 0.2388} \quad (4.7)
\]

To compare these functions and those of Usui, they are plotted for the four cutting speeds used during the experiments. The shear angle (figure 4.12) is found to be more dependent on the cutting speed and feed rate than in Usui’s experiments.

\[\text{figure 4.11 - friction angle measurement result}\]
The most significant difference in the shear stress (figure 4.13) seems to be a larger offset value. Here it can be assumed that the higher cutting speed and feed rate dependency of the shear angle are caused by a difference in chip thickness measurements, the difference in shear stress is probably mostly due to different work piece material.
The friction angle (figure 4.14) turns out to be much less dependent on the cutting speed than the findings of E. Usui. It is unclear where these differences originate from.

As a final test the results are compared with a second empirical relation. In literature [7] the force on the rake face of the tool is assumed to vary exponentially with the feed rate and cutting speed and linearly or sinusoidally with the rake angle (4.8, 4.9). Since the rake angle in the experiments is zero the forces parallel ($P$) and normal ($N$) to the rake face are equal to the feed force ($F_f$) and tangential force ($F_t$) respectively.

\[ N = b C_1 V^{a_1} a^{b_1} (1 - \sin \alpha)^{c_1} \tag{4.8} \]

\[ P = b C_2 V^{a_2} a^{b_2} (1 - \sin \alpha)^{c_2} \tag{4.9} \]

The parameters for steel 1018 are used. The results are plotted in figure 4.15. While the empirical relation from the literature shows close agreement for the forces in radial direction (feed force), the prediction of the tangential force is less accurate.
Figure 4.15 - Comparison with second empirical relation
5 Oscillation tests

On the same lathe oscillating cutting experiments are performed using the piezo actuated tool (figure 4.1). This oscillation closely resembles the regenerative chatter process. The first test of the usability of the model for chatter prediction modeling is comparing it with the result from the oscillating cutting test. The prediction of cutting forces during oscillation using the model is explained in chapter 5.1. The comparison with the experimental measurements is shown in chapter 5.2.

5.1 Oscillating cutting model

The cutting force model created in Matlab is used to predict the cutting forces during regenerative chatter. The system is assumed to be in steady vibration creating a modulation in the feed rate. The modulation from the previous cut (inner modulation) and from the tool (outer modulation) are taken into account. The modulation results in changing rake angle and variations in the shear and friction angle. These variations in turn result in changes in the cutting force, which can be observed in figure 5.1.

![figure 5.1 - oscillating cutting modeling](image)

5.2 Comparing the force model

During the creation of the model, the oscillating cutting tool was used to perform oscillating cutting tests. By using a piezo servo and a laser nano sensor, the tool can be accurately actuated. The resulting force measurements are plotted against the modeled forces from chapter 4.1. As can be observed the measured forces are a factor 1.5 higher and there is a slight shift in phase.
Part of this difference can be caused by noise in the signal. Therefore a zero phase low pass filter was used to filter the measured force signal. Furthermore the response of the signal to the input wavelength was determined using a Fourier transformation. The results thereof can be seen in figure 5.3. The model seems to be more accurate for short wavelengths, i.e. high oscillation frequencies.
6 Conclusions and Recommendations

The production speed in modern day production lines is most often limited by chatter occurrence. Current dynamic machining theory however only has limited accuracy in predicting chatter, especially at low speeds. Therefore improvement of these theories and the accompanying models is of vital importance. The work and model described in this report is a small contribution, but will hopefully prove to be useful for further research. During the experiments various influences on the dynamic cutting process are examined and their importance determined: the material hardness and the tool tip radius. The hardness of the material is homogeneous and constant throughout the cutting process and therefore has little influence on cutting dynamics. The tool tip radius renders the results unusable when it reaches 1/3 of the feedrate. Using these results the feedrate range of the model is determined and by comparing the results with existing empirical models the accuracy and credibility of the model is determined. The comparison of the model with oscillating cutting data however shows a major force factor is still missing in the model. The result is a factor 2 difference in magnitude and slight shift in phase. This is probably mainly due to the fact that the edge coefficients, or friction forces, are not included into the model. Furthermore the accuracy of the spindle speed of the superslant lathe is to low and needs to be improved.
Literature


Appendix A  First Test Results

The first tests show very irregular results. Cutting measurements are performed at spindle speeds of 500, 1000, 1500, 2000 and 2500 [rpm] and federates of 0.01, 0.02, 0.03, 0.04 and 0.05 [mm/rev]. The work piece consists of a bar of 1018 steel. The insert was Carbide Tungsten. The material was cut from a diameter of 38.10 [mm] to 34.10 [mm].

![Radial Cutting Force](image)

*figure A.1*

![Tangential Cutting Force](image)

*figure A.2*
Appendix B  Dynamometer sensitivity measurements

The sensitivity of the piezo actuated dynamometer shows undesirable sensitivity next to the anticipated sensitivity peaks (see figure 31). The first peak (at ± 600 Hz.) in the output spectrum is the desired sensitivity for forces in the measured direction. Secondary peaks however should not come within the range of the first peak. This is the case with the piezo actuated dynamometer, making it unsuitable to use for the force measurements. Most likely this is caused by zero charge on the piezo. During oscillating measurements the piezo element is charged and thereby actuated, making it stiffer. It was not possible to charge the piezo in such a way as to make it stay in 1 position. Therefore the piezo actuated dynamometer was replaced with a stiffer dynamometer.

![Input Spectrum (Acc)](image1)

![Output Spectrum (Acc)](image2)

*figure B.1 - piezo actuated dynamometer sensitivity measurement*
The new dynamometer showed better results (see figure 32). The secondary peaks are much smaller than with the previous.

Figure B.2 - replacement dynamometer sensitivity measurement
## Appendix C  Dynamometer calibration

<table>
<thead>
<tr>
<th>Impact Hammer measurement</th>
<th>Radial Direction (X)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>plastic tip #1</td>
<td>plastic tip #2</td>
<td>plastic tip #3</td>
<td>metal tip</td>
<td>soft plastic tip</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>0,95</td>
<td>1,05</td>
<td>0,99</td>
<td>0,89</td>
<td>1,15</td>
<td>1,01</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>0,04</td>
<td>0,09</td>
<td>0,10</td>
<td>0,02</td>
<td>0,03</td>
<td>0,06</td>
<td></td>
</tr>
<tr>
<td>Z</td>
<td>0,01</td>
<td>0,26</td>
<td>0,20</td>
<td>-0,20</td>
<td>-0,20</td>
<td>0,01</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Axial Direction (Y)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>plastic tip #1</td>
<td>plastic tip #2</td>
<td>plastic tip #3</td>
<td>metal tip</td>
<td>soft plastic tip</td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>0,00</td>
<td>0,05</td>
<td>0,00</td>
<td>-0,12</td>
<td>-0,01</td>
<td>-0,02</td>
</tr>
<tr>
<td>Y</td>
<td>0,61</td>
<td>0,64</td>
<td>0,59</td>
<td>0,53</td>
<td>0,76</td>
<td>0,63</td>
</tr>
<tr>
<td>Z</td>
<td>0,05</td>
<td>0,19</td>
<td>-0,03</td>
<td>-0,38</td>
<td>0,00</td>
<td>-0,03</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tangential Direction (Z)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>plastic tip #1</td>
<td>plastic tip #2</td>
<td>plastic tip #3</td>
<td>metal tip</td>
<td>soft plastic tip</td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>0,11</td>
<td>0,01</td>
<td>-0,03</td>
<td>0,05</td>
<td>0,05</td>
<td>0,04</td>
</tr>
<tr>
<td>Y</td>
<td>0,28</td>
<td>0,24</td>
<td>0,23</td>
<td>0,28</td>
<td>0,39</td>
<td>0,28</td>
</tr>
<tr>
<td>Z</td>
<td>1,10</td>
<td>0,83</td>
<td>0,68</td>
<td>0,90</td>
<td>1,36</td>
<td>0,97</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Static force measurement</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>no weight</td>
<td>10 lbs</td>
<td>20 lbs</td>
<td>30 lbs</td>
<td>40 lbs</td>
<td>50 lbs</td>
<td>60 lbs</td>
</tr>
<tr>
<td>weight (kg)</td>
<td>0,00</td>
<td>1,26</td>
<td>5,79</td>
<td>10,33</td>
<td>14,87</td>
<td>19,40</td>
<td>23,94</td>
</tr>
<tr>
<td>force (N)</td>
<td>0,00</td>
<td>12,35</td>
<td>56,85</td>
<td>101,35</td>
<td>145,84</td>
<td>190,34</td>
<td>234,84</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Radial Direction (X)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>1,2</td>
<td>10,9</td>
<td>54,0</td>
<td>98,0</td>
<td>141,6</td>
<td>184,5</td>
</tr>
<tr>
<td>Y</td>
<td>0,5</td>
<td>0,8</td>
<td>1,2</td>
<td>1,5</td>
<td>1,8</td>
<td>2,1</td>
</tr>
<tr>
<td>Z</td>
<td>-1,2</td>
<td>-0,1</td>
<td>0,3</td>
<td>0,6</td>
<td>1,0</td>
<td>1,4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Axial Direction (Y)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>-1,0</td>
<td>5,6</td>
<td>35,2</td>
<td>65,5</td>
<td>96,5</td>
<td>127,0</td>
</tr>
<tr>
<td>Y</td>
<td>-1,6</td>
<td>-4,5</td>
<td>-6,9</td>
<td>-9,0</td>
<td>-10,5</td>
<td>-12,3</td>
</tr>
<tr>
<td>Z</td>
<td>0,0</td>
<td>12,3</td>
<td>56,3</td>
<td>98,5</td>
<td>141,7</td>
<td>184,7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tangential Direction (Z)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>0,2</td>
<td>0,2</td>
<td>0,2</td>
<td>0,1</td>
<td>0,1</td>
<td>0,1</td>
</tr>
<tr>
<td>Y</td>
<td>0,3</td>
<td>3,3</td>
<td>13,5</td>
<td>22,8</td>
<td>32,2</td>
<td>40,4</td>
</tr>
<tr>
<td>Z</td>
<td>0,0</td>
<td>12,3</td>
<td>56,3</td>
<td>98,5</td>
<td>141,7</td>
<td>184,7</td>
</tr>
</tbody>
</table>

---
Appendix D  Error analysis of chip thickness measurements

Estimations of the measuring error were distinguished between small and large coils and individual chips. This resulted in the lowest error for individual chips and highest for large coils.

<table>
<thead>
<tr>
<th>Estimated errors</th>
<th>min</th>
<th>max</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>small coils</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>length variation</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>diameter variation</td>
<td>0,2</td>
<td></td>
</tr>
<tr>
<td>average # turns</td>
<td>13,04</td>
<td>13,04</td>
</tr>
<tr>
<td>average length</td>
<td>33,86</td>
<td>32,86</td>
</tr>
<tr>
<td>average diameter</td>
<td>3,87</td>
<td>3,67</td>
</tr>
<tr>
<td>average coil length</td>
<td>161,93</td>
<td>153,71</td>
</tr>
<tr>
<td>error</td>
<td>94,93</td>
<td>105,08</td>
</tr>
<tr>
<td><strong>large coils</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>length variation</td>
<td>0,50</td>
<td></td>
</tr>
<tr>
<td>diameter variation</td>
<td>1,00</td>
<td></td>
</tr>
<tr>
<td>average # turns</td>
<td>4,98</td>
<td>4,98</td>
</tr>
<tr>
<td>average length</td>
<td>35,41</td>
<td>34,91</td>
</tr>
<tr>
<td>average diameter</td>
<td>11,40</td>
<td>10,40</td>
</tr>
<tr>
<td>average coil length</td>
<td>181,95</td>
<td>166,52</td>
</tr>
<tr>
<td>error</td>
<td>91,52</td>
<td>108,50</td>
</tr>
<tr>
<td><strong>chips</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>length variation [mm]</td>
<td>0,50</td>
<td></td>
</tr>
<tr>
<td>average length [mm]</td>
<td>12,51</td>
<td>12,01</td>
</tr>
<tr>
<td>error [%]</td>
<td>96,00</td>
<td>104,00</td>
</tr>
<tr>
<td><strong>weight</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>variation</td>
<td>0,00</td>
<td></td>
</tr>
<tr>
<td>small coils</td>
<td>0,41</td>
<td>0,41</td>
</tr>
<tr>
<td>error [%]</td>
<td>99,88</td>
<td>100,12</td>
</tr>
<tr>
<td>large coils</td>
<td>1,55</td>
<td>1,55</td>
</tr>
<tr>
<td>error [%]</td>
<td>99,97</td>
<td>100,03</td>
</tr>
<tr>
<td>chips</td>
<td>0,52</td>
<td>0,52</td>
</tr>
<tr>
<td>error [%]</td>
<td>99,90</td>
<td>100,10</td>
</tr>
</tbody>
</table>

TO KEEP ERRORS LESS THAN 5%:
MINIMUM CHIP LENGTH: 10 mm
MINIMUM WEIGHT: 0.01 g
Appendix E  Dytran impulse hammer

<table>
<thead>
<tr>
<th>MODEL NO.</th>
<th>SENSOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>5800B2</td>
<td>100 mV/lbf</td>
</tr>
<tr>
<td>5800B3</td>
<td>50 mV/lbf</td>
</tr>
<tr>
<td>5800B4</td>
<td>10 mV/lbf</td>
</tr>
<tr>
<td>5800B5</td>
<td>5 mV/lbf</td>
</tr>
</tbody>
</table>

SPECIFICATIONS, MODEL SERIES 5800B DYNAPULSE® IMPULSE HAMMERS

<table>
<thead>
<tr>
<th>MODEL</th>
<th>RANGE FOR ±5V OUT</th>
<th>SENSITIVITY</th>
<th>MAX. FORCE</th>
<th>DISCHARGE TIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>5800B2</td>
<td>50</td>
<td>100</td>
<td>1000</td>
<td>20</td>
</tr>
<tr>
<td>5800B3</td>
<td>100</td>
<td>50</td>
<td>1000</td>
<td>50</td>
</tr>
<tr>
<td>5800B4</td>
<td>500</td>
<td>10</td>
<td>1000</td>
<td>170</td>
</tr>
<tr>
<td>5800B5</td>
<td>1000</td>
<td>6</td>
<td>2000</td>
<td>300</td>
</tr>
</tbody>
</table>

COMMON SPECIFICATIONS, ALL MODELS

<table>
<thead>
<tr>
<th>SPECIFICATION</th>
<th>VALUE</th>
<th>UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>FULL SCALE OUTPUT VOLTAGE</td>
<td>5</td>
<td>VOLTS</td>
</tr>
<tr>
<td>STIFFNESS, SENSOR</td>
<td>11.4</td>
<td>Lb Ftl</td>
</tr>
<tr>
<td>RESONANT FREQUENCY</td>
<td>75</td>
<td>kHz</td>
</tr>
<tr>
<td>LINEARITY</td>
<td>±1</td>
<td>%FS</td>
</tr>
<tr>
<td>OUTPUT IMPEDANCE, MAX</td>
<td>100</td>
<td>Ohms</td>
</tr>
<tr>
<td>VOLTAGE BIAS, NOM</td>
<td>+10</td>
<td>VDC</td>
</tr>
<tr>
<td>SUPPLY (COMPLIANCE) VOLTAGE RANGE</td>
<td>+18 TO +30</td>
<td>VDC</td>
</tr>
<tr>
<td>SUPPLY CURRENT RANGE</td>
<td>2 TO 20</td>
<td>mA</td>
</tr>
<tr>
<td>MATERIAL, HEAD/HANDLE</td>
<td>STAINLESS STEEL/FIBERGLAS</td>
<td></td>
</tr>
<tr>
<td>WEIGHT, HEAD 6900A</td>
<td>100</td>
<td>Grams</td>
</tr>
<tr>
<td>CONNECTOR</td>
<td>BNC JACK</td>
<td>COAXIAL</td>
</tr>
</tbody>
</table>

ACCESSORIES SUPPLIED WITH BASIC HAMMER

(1) Impact tips, Model 6250A (aluminum), (1) Model 6250P (plastic) and (1) 6250PS, (soft plastic)

Accessories supplied with hammer kits HB5800B, HL5800B:
above tips plus (2) head extenders, 627051 and 627052 for Model series 5800B.
Appendix F  Contour Tracer

The edge radii of several tungsten-carbide inserts (Sandvik BG154.91-3 H13A) were measured using a contour tracer (figure F.1 and F.2).

---

**figure F.1 The contour tracer**

---

**figure F.2 the diamond stylus used during measurements**
Appendix G  Hall Sensor

Honeywell

4AV16F

4AV Series Hall-Effect Vane with 24 AWG XLPE 189,2 mm [7.45 in] lead wires

Features

- Current sinking output
- Smaller size than 2AV
- Closely controlled differential to predict pulse width
- Operation by a low cost, easy to fabricate ferrous vane
- Magnet and sensor incorporated in same rugged package
- Sealed construction ... unaffected by dust or dirt
- 0 kHz to 100 kHz operating speed ... no minimum speed of operation
- On and Off times programmable by vane dimensioning
- Precision mechanical operating characteristics

Description

AV vane operated integral magnet position sensors are operated by passing a ferrous vane through the gap between the Hall sensor and the magnet, shunting the magnetic flux away from the sensor. AVs can be used as limit switches by operating with a single large vane; as tachometer sensors by using toothed wheels; or as synchronizing elements by using cams or sectors.

Honeywell

4AV16F

4AV Series Hall-Effect Vane with 24 AWG XLPE 189,2 mm [7.45 in] lead wires

<table>
<thead>
<tr>
<th>Product Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Product Type</strong></td>
</tr>
<tr>
<td><strong>Package Style</strong></td>
</tr>
<tr>
<td><strong>Supply Voltage</strong></td>
</tr>
<tr>
<td><strong>Output Type</strong></td>
</tr>
<tr>
<td><strong>Termination Type</strong></td>
</tr>
<tr>
<td><strong>Operating Temperature Range</strong></td>
</tr>
<tr>
<td><strong>Output Voltage</strong></td>
</tr>
<tr>
<td><strong>Vibration</strong></td>
</tr>
</tbody>
</table>

Appendix H  Detecting Chatter using CUTpro

figure H.1
Appendix I  Matlab model

```matlab
close all
clear all
clic

Oscillation_tests = ('D:\EXTERNE STAGE\Tests\Test 5 (feb 13)\Oscillation_tests.xls');
Shear_tests = ('D:\EXTERNE STAGE\Tests\Test 5 (feb 13)\Shear_tests.xls');
Testdata = ('D:\EXTERNE STAGE\Tests\Test 5 (feb 13)\Test 5\Oscillation Tests\');
[freq, filename] = xlsread(Oscillation_tests,'Sheet1','A19');
filename = strcat(Testdata, filename, 'mdt');
spindlespeed = xlsread(Oscillation_tests,'Sheet1','B19');
freq = xlsread(Oscillation_tests,'Sheet1','F19');
feedrate = xlsread(Oscillation_tests,'Sheet1','L19');
width = 1e-3*0.5;

phi_V = xlsread(Shear_tests,'Shear Angle','C25');
.phi_f = xlsread(Shear_tests,'Shear Angle','C26');
.phi_c = xlsread(Shear_tests,'Shear Angle','C27');
tau_V = xlsread(Shear_tests,'Shear Stress','C25');
tau_f = xlsread(Shear_tests,'Shear Stress','C26');
tau_c = xlsread(Shear_tests,'Shear Stress','C27');

fprintf('parameters loaded
')
for i= 1:length(filename)
    Data = load(char(filename(i)));
    time(1:length(Data),i) = Data(:,1);
    Fx_raw(1:length(Data),i) = Data(:,2);
    Fy_raw(1:length(Data),i) = Data(:,3);
    Fz_raw(1:length(Data),i) = Data(:,4);
    Disp_raw(1:length(Data),i) = Data(:,5);
    SN(1:length(Data),i) = sin(2*pi*freq(i)*time(1:length(Data),i));
    CN(1:length(Data),i) = cos(2*pi*freq(i)*time(1:length(Data),i));

    fprintf('loaded %s.mdt
',char(filename(i)))
clear Data
end
load Lowpass.mat
fprintf('Data loaded
')
Fx_filt = filtfilt(Lowpass,1,Fx_raw);
Fy_filt = filtfilt(Lowpass,1,Fy_raw);
Fz_filt = filtfilt(Lowpass,1,Fz_raw);
Disp_filt = filtfilt(Lowpass,1,Disp_raw);
fprintf('Data filtered
')
Fx_mag = abs((SN.*Fx_filt +1j*CN.)*Disp_filt)/(SN.*Disp_filt+1j*CN.*Disp_filt));
Fx_phase = angle((SN.*Fx_filt +1j*CN.)*Disp_filt)/(SN.*Disp_filt+1j*CN.*Disp_filt));
Fy_mag = abs((SN.*Fy_filt +1j*CN.)*Fy_filt)/(SN.*Fy_filt+1j*CN.*Fy_filt));
Fy_phase = angle((SN.*Fy_filt +1j*CN.)*Fy_filt)/(SN.*Fy_filt+1j*CN.*Fy_filt));
Fz_mag = abs((SN.*Fz_filt +1j*CN.)*Fz_filt)/(SN.*Fz_filt+1j*CN.*Fz_filt));
Fz_phase = angle((SN.*Fz_filt +1j*CN.)*Fz_filt)/(SN.*Fz_filt+1j*CN.*Fz_filt));
Disp_mag = abs(SN.*Disp_filt +1j*CN.)*Disp_filt);
Disp_phase = angle(SN.*Disp_filt +1j*CN.)*Disp_filt);

fprintf('Data processed
')
rake = 0;
diameter = 38.1e-3;
Vsurf = (diameter*pi*spindlespeed/60);
L = length(time);
Dy(2:L,1) = 1e-6*(Disp_raw(2:L,1)-Disp_raw(1:L-1,1));
Dy(1,1) = 1e-6*(Disp_raw(2,1)-Disp_raw(1,1));
Vfeed = [Dy./(time(2)-time(1))];
Vcut = (Vsurf^2+Vfeed.^2).^0.5;
```

---

41
alpha = rake+atan(Vfeed./Vsurf);
onerev = (60/spindlespeed)/(time(2)-time(1));
onerev = onerev+0.00*onerev;
outermod(1:onerev,1) = zeros(onerev,1);
outermod(onerev+1:length(time),1) = 1e-6*Disp_raw(1:length(time)-onerev);
innermod = Disp_raw*le-6;
feed = feedrate-innermod+outermod;
phi = exp(phi_V*Vcut+phi_f*feed*1000+phi_c);
beta = exp(beta_V*Vcut+beta_f*feed*1000+beta_c);
tau = exp(tau_V*Vcut+tau_f*feed*1000+tau_c);
As = width*(feed./sin(phi));
Kf = (tau.*sin(beta-alpha))./(sin(phi).*cos(phi+beta-alpha));
Kt = (tau.*cos(beta-alpha))./(sin(phi).*cos(phi+beta-alpha));
Ffm = Kf.*feed.*width+Kt.*feed.*width.*Vfeed./Vsurf;
Fm = (tau.*As*le6)./cos(phi+beta-alpha);
Fm_fi lt = filtfilt(Lowpass,1,Fm);
Fm_mag = abs((SN.'*Fm_fi lt +1j*CN.'*Fm_fi lt)/(SN.'*Disp_fi lt +1j*CN.'*Disp_fi lt));
Fm_phase = angle((SN.'*Fm_fi lt +1j*CN.'*Fm_fi lt)/(SN.'*Disp_fi lt +1j*CN.'*Disp_fi lt));
inwwavelength = freq/Vsurf;
figure(1)
plot(time,Fm_fi lt,time,Fx_fi lt,time,Fy_fi lt,time,Fz_fi lt)
xlabel('time [s]')
ylabel('Force [N]')
xlim([0 1])
legend('F_m', 'F_x', 'F_y', 'F_z')
figure(2)
plot(time,Fm,time,Fx_fi lt,time,Fy_fi lt,time,Fz_fi lt)
xlabel('time [s]')
ylabel('Force [N]')
legend('F_m', 'F_x', 'F_y', 'F_z')
figure(3)
plot(time,Disp_fi lt,time,le6*feed,time,le6*innermod,time,le6*outermod)
xlim([0 1])
xlabel('time [s]')
ylabel('displacement [\mum]')
legend('Disp_-filt','feed','innermod','outermod')