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Comparison of methods for on-line calibration of cutting force models in end milling

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COMPARISON OF METHODS FOR ON-LINE CALIBRATION OF CUTTING FORCE MODELS IN END MILLING

by

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B.S., Huazhong University of Science and Technology, 2010

THESIS

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LIST OF SYMBOLS

\( \phi \) = edge locating angle of cutting tool, (rad)

\( h \) = chip thickness, (mm)

\( c \) = feed per tooth, (mm)

\( \psi \) = lag angle, (rad)

\( \beta \) = helix angle of cutting tool, (rad)

\( D \) = tool diameter, (mm)

\( \omega_n \) = natural frequency, (Hz)

\( \omega \) = spindle speed, (rpm)

\( P_v \) = available cutting power, (watt)

\( P_e \) = electrical power input into the spindle motor, (watt)

\( \eta_e \) = motor efficiency

\( P_f \) = frictional power, (watt)

\( E_o \) = output voltage from the LCI power sensor, (volt)

\( K_p \) = the sensitivity of the LCI sensor, (watt/volt)

\( K_s \) = the motor-sensor system sensitivity, (watt/volt)

\( E_t \) = tare power voltage, (volt)

\( h_a \) = average chip thickness, (mm)

\( \phi_e \) = angle at which tooth enters material, (rad)

\( \phi_{es} \) = angle at which tooth exits material, (rad)
\( Q \) = volumetric removal rate, \((\text{mm}^3/\text{s})\)

\( A_i \) = contact area rate, \((\text{mm}^2/\text{s})\)

\( G \) = geometry matrix related to the cut geometry

\( N \) = number of teeth on the cutting tool

\( a \) = axial depth of cut, \((\text{mm})\)

\( K_{rc} \) = model coefficient for radial shearing force component, \((\text{N/mm}^2)\)

\( K_{re} \) = model coefficient for radial friction force component, \((\text{N/mm})\)

\( K_{tc} \) = model coefficient for tangential shearing force component, \((\text{N/mm}^2)\)

\( K_{te} \) = model coefficient for tangential friction force component, \((\text{N/mm})\)

\( F_r \) = radial force on the tool, \((\text{N})\)

\( F_t \) = tangential force on the tool, \((\text{N})\)

\( F_{res} \) = resultant force on the tool, \((\text{N})\)

\( F_x \) = force on the tool in the \(x\)-direction, \((\text{N})\)

\( \overline{F_x} \) = average force in the \(x\)-direction, \((\text{N})\)

\( F_y \) = force on the tool in the \(y\)-direction, \((\text{N})\)

\( \overline{F_y} \) = average force in the \(y\)-direction, \((\text{N})\)

\( \overline{F} \) = vector of average forces in \(x\) and \(y\) direction

\( K \) = force model coefficient vector

\( \text{RE}_p \) = relative error of the peak force
ABSTRACT

COMPARISON OF METHODS FOR ON-LINE CALIBRATION OF CUTTING FORCE MODELS IN END MILLING

by

Yong Zhao

University of New Hampshire, May 2012

Accurate estimation of cutting coefficients is extremely important in end milling process modeling, and it forms the basis of a smart machining system that can be used for process planning and monitoring. Specific applications include feedrate selection based on force constraints and monitoring of tool wear [1, 2].

This thesis investigates five different methods to calibrate the cutting force model coefficients in end milling processes and compares them in terms of cost, efficiency, compliance, accuracy, repeatability and applicability. The five methods are based on: 1. spindle motor power, 2. Kistler average force, 3. Kistler force profile, 4. Smart Tool average force and 5. Smart Tool force profile. Three different sensors are used in the calibration processes: 1. a spindle motor power sensor purchased from Load Control Inc, 2. a Kistler dynamometer which measures the workpiece reaction force in the X and Y directions and 3. a wireless Smart Tool which measures tangential and radial cutting forces on the tool. For the power sensor, only average power is available to calibrate the
cutting coefficients, while for the Kistler dynamometer and the Smart Tool, both average force and force profiles are used to calibrate the cutting coefficients.

Applicability and limitations of each calibration method are discussed, and general conclusions are made for on-line calibration.
CHAPTER 1

INTRODUCTION

1.1 Introduction

Accurate estimation of cutting coefficients is extremely important in end milling process modeling, and it forms the basis of a smart machining system that can be used for process planning and monitoring. Specific applications include feedrate selection based on force constraints and monitoring of tool wear [1, 2].

There are various methods to calibrate cutting coefficients. Budak et al. presented a unified mechanistic model for estimating the cutting coefficients for cylindrical helical end mills [3]. It is shown that the cutting coefficients for all force components and cutter geometries can be predicted from an orthogonal cutting database and a generic oblique cutting analysis. Lee et al. further extended the approach to helical ball end mills [4]. The distribution of cutting force on the helical ball end mill flutes is accurately predicted by the proposed method. However, some cutting tools may have complex geometry, and the evaluation of cutting constants by creating a time-consuming orthogonal cutting database may not be practical.

The model coefficients can also be identified through an empirical curve fit to measured average milling power, average forces, or instantaneous forces. The least squares fit method is widely used in force model calibration by trying to either fit the average power or force for a number of cuts, or the instantaneous cutting force of one
specific cut [5-9]. Although power sensors are cheap, easy to implement and noninvasive, only tangential cutting coefficients can be obtained from the average power method [5]. To use average power or average force based calibration method [5, 6], typically, a set of milling experiments are conducted at different feedrates with constant spindle speed, radial immersion and axial depth of cut to provide different average chip thicknesses. However, there is a major limitation with this calibration process. Since average power or force is used to calibrate the cutting coefficients, there need to be at least two different cutting conditions to generate two different average chip thicknesses to realize the calibration. Thus, one cannot get the cutting coefficients from any cutting test having the same cutting condition, which limits its practicality.

Other researchers used the instantaneous force profile measured from a single cutting test to predict the cutting coefficients, but their methods are based on a much more complicated model that requires significant knowledge of the tool geometry and synchronization of the measured and simulated cutting forces, making their calibration methods somewhat limited for on-line calibration [7-9]. By investigating milling forces in the frequency domain, Zhang et al. provided an improved method to calibrate the cutting coefficients [10]. The validity of the method is confirmed based on a series of experiments and numerical simulations.

In this thesis, five different calibration methods are introduced and compared. They are based on: 1. spindle motor power, 2. Kistler average force, 3. Kistler force
profile, 4. Smart Tool average force and 5. Smart Tool force profile. Each calibration method is described in details in Chapter 5.

1.2 Thesis Overview

Chapter 1 is an introduction to force model calibration. Chapter 2 introduces the cutting force model used in this research as well as the three different sensors used for force model calibration: LCI power sensor, Kistler dynamometer and wireless Smart Tool.

Chapter 3 describes the spindle motor characterization experiment to determine the motor-sensor system sensitivity at each spindle speed, information necessary to estimate cutting power from the measured spindle motor power. Experimental setup and discussion of experiment results are included in this chapter.

Chapter 4 introduces the cutting test design. Low spindle speed of 600 rpm and high spindle speed of 3000 rpm cutting tests are designed and conducted in this research. Chapter 5 describes the aforementioned five calibration methods in detail.

In Chapter 6, cutting coefficient calibration results of the five different methods are shown and compared. The simulated cutting force using the calibrated coefficients from each method is compared to the force measured by the Kistler dynamometer. The comparison of the five different calibration methods in terms of cost, efficiency, compliance, accuracy, repeatability and applicability is also included. Chapter 7 summarizes the outcomes of this research and offers suggestions for future work.
CHAPTER 2

BACKGROUND

2.1 Introduction

In this chapter, the milling force model used in this research is introduced. The three different sensors used for force model calibration are also introduced. They are the LCI power sensor, Kistler dynamometer and Smart Tool respectively.

2.2 Force Model

The mechanistic milling force model used in this research is described by Altintas [11]. The tangential and radial force consists of a shearing component and a rubbing, ploughing or friction component. Compared to other more complicated models [12], this linear model is simple to calibrate and extensive testing in our facility has demonstrated good accuracy and repeatability as long as the model is calibrated correctly [6]. Figure 2.1 defines a general cutting geometry for end milling.

Figure 2.1 - End Milling Cutting Geometry [13]
For simplicity, only flat-end milling cutters with a single cutting tooth are considered in this thesis, and the force component in the axial or Z direction is ignored. Although the calibration method relies on the use of a single tooth cutter, the cutting coefficients obtained by the process can be applied to multi-tooth cutters. Tangential (\(dF_t\)) and radial (\(dF_r\)) forces acting on a differential tooth element with height \(dz\) are expressed as [11]:

\[
dF_t(\phi, z) = [K_{tc}h(\phi(z)) + K_{tr}]dz
\]

\[
dF_r(\phi, z) = [K_{rc}h(\phi(z)) + K_{re}]dz
\]

where \(K_{tc}\) and \(K_{te}\) are tangential cutting coefficients, \(K_{rc}\) and \(K_{re}\) are radial cutting coefficients, \(\phi(z)\) is the edge locating angle, and the chip thickness is:

\[
h(\phi(z)) = c \sin(\phi(z))
\]

where \(c\) is the feed per tooth (mm/tooth). Assuming that the bottom of the tooth is designated as the reference locating angle \(\phi_l\), at an axial depth of cut \(z\) the lag angle is \(\psi = k_\mu z\), where \(k_\mu = 2\tan(\beta) / D\), \(\beta\) is the helix angle, and \(D\) is the diameter of the cutting tool. The locating immersion angle for the tooth at the axial depth of cut \(z\) is:

\[
\phi(z) = \phi_l - k_\mu \cdot z
\]

The elemental forces are resolved into feed (x) and normal (y) directions using the transformation:

\[
dF_x(\phi(z)) = -dF_t \cos(\phi(z)) - dF_r \sin(\phi(z))
\]

\[
dF_y(\phi(z)) = +dF_t \sin(\phi(z)) - dF_r \cos(\phi(z))
\]
Substituting the differential forces (Equations 2.1 and 2.2) and chip thickness (Equation 2.3) into Equations 2.5 and 2.6 leads to:

\[
dF_x(\phi(z)) = \frac{c}{2} \left[ -K_u \sin 2\phi(z) - K_n (1 - \cos 2\phi(z)) \right] dz
\]

\[
dF_y(\phi(z)) = \frac{c}{2} \left[ K_n (1 - \cos 2\phi(z)) - K_n \sin 2\phi(z) \right] dz
\]

The differential cutting forces are integrated analytically along the in-cut portion of the tooth in order to obtain the total cutting force acting on the tooth:

\[
F_q(\phi(z)) = \int_{z_1}^{z_2} dF_q(\phi(z)), \quad q = x, y
\]

where \(z_1(\phi(z))\) and \(z_2(\phi(z))\) are the lower and upper axial engagement limits of the in-cut portion of the tooth. The integrations are carried out by noting \(\phi(z) = \phi_1 - k_p z\), \(d\phi(z) = -k_p dz\). Thus:

\[
F_x = \left\{ \frac{c}{4k_p} (-K_n \cos 2\phi) + \frac{1}{k_p} K_n \sin \phi + \frac{c}{4k_p} [K_n (2\phi - \sin 2\phi)] + \frac{1}{k_p} (-K_n \cos \phi) \right\}_{z_1(\phi(z))}^{z_2(\phi(z))}
\]

\[
(2.10)
\]

\[
F_y = \left\{ \frac{c}{4k_p} [-K_n (2\phi - \sin 2\phi)] + \frac{1}{k_p} K_n \cos \phi + \frac{c}{4k_p} [-K_n \cos 2\phi] + \frac{1}{k_p} (K_n \sin \phi) \right\}_{z_1(\phi(z))}^{z_2(\phi(z))}
\]

\[
(2.11)
\]
2.3 Sensor Introduction

Three different sensors have been used in this research. They are the LCI power sensor, the Kistler dynamometer and the Smart Tool respectively. Each sensor is briefly introduced as below.

2.3.1 LCI Power Sensor

Model UPC from Load Control Incorporated (LCI) has been used to measure the electrical power input into the spindle motor. The LCI power sensor provides an analog output of 0-10 volts proportional to the spindle motor power with an accuracy of 0.5% full scale [14]. The LCI power sensor is non-invasive and easy to install. The low cost ($650) and non-invasive nature of the sensor make it ideal for the shop floor environment. The time constant is about 25 ms which was evaluated by measuring the power signal of a step input [15]. With known LCI sensor sensitivity and CNC spindle motor efficiency, good force model coefficients estimation is possible [1, 2, 5, 15]. For our model calibration in this research, we treat the spindle motor efficiency and LCI sensitivity
together, as an overall spindle motor power sensor system sensitivity. The calibration of this system and its use is described in Chapter 3.

2.3.2 Kistler Dynamometer

Figure 2.3 - Kistler Dynamometer

The Kistler dynamometer used in this research is model number 9257B. It is a three-component dynamometer for measuring three orthogonal components of a force and has great rigidity (stiffness $>10^9$ N/m in the X and Y direction) and consequently a high natural frequency (2.3 KHz in the X and Y direction if it is mounted on its flanges). Its high resolution enables the smallest dynamic changes in large forces to be measured. It has a range of -5 kN to +5 kN for all the three force components with a linearity of 1% full scale [16].

If a workpiece is mounted on the top plate of the dynamometer, then according to

$$\omega_0 = \sqrt{\frac{k}{m}},$$

its natural frequency will be decreased. By doing tap tests in both X and Y directions of the dynamometer with the workpiece attached, we find its natural frequency around 1000 Hz in both directions.
Figure 2.4 shows a typical frequency response curve of the Kistler dynamometer. As shown, a 5% amplitude rise can be expected at approximately 1/5 of the resonant frequency [16]. Of course it is also noted that some phase delay will occur if the signal measured by the dynamometer has frequency components near its natural frequency. Therefore in our case, the Kistler dynamometer can work well in a frequency range up to approximately 200 Hz. Overall, the Kistler is a high quality sensor and has been widely used in academic research in machining for many years. It is not a practical choice for use in industry due to its high cost (~$35K) and invasive nature.

2.3.3 Smart Tool

Figure 2.4 - Typical Frequency Response Curve of Kistler [16]

Figure 2.5 - Smart Tool
The Smart Tool is a custom-designed wireless sensor that is used to measure tangential and radial forces. Semi-conductor strain gages mounted on the tool holder shank produce a signal proportional to cutting force when measured statically. It is statically calibrated to measure tangential and radial forces up to 1334.5 N (300 lb) with an accuracy of 5% full scale. The Smart Tool has a natural frequency of approximately 650 Hz, a stiffness of $5 \times 10^6$ N/m, and a static sensitivity of 23.5 bits/N for a 16-bit A/D chip [17]. One of the important goals of this research is to determine if the Smart Tool can provide “Kistler like” information at a cost and convenience that is closer to that of the LCI power sensor.

2.4 Summary

In Chapter 2, the milling force model used in this research is introduced. The three different sensors used for force model calibration are also briefly introduced. They are the LCI power sensor, the Kistler dynamometer and the Smart Tool respectively.
CHAPTER 3

SPINDLE MOTOR POWER SENSOR SYSTEM CALIBRATION

3.1 Introduction

Accurate cutting power is the most critical factor for obtaining good force model coefficients using the power model calibration method [15]. In order to get accurate cutting power, an experiment was designed to characterize the relationship between the cutting power and the signal from the Load Control Inc (LCI) power sensor. This chapter describes the spindle motor power sensor system sensitivity calibration at each spindle speed, which can then be used to estimate the actual cutting power at the tool from the LCI sensor output. The LCI sensor output is proportional to the electrical input power to the motor and the system sensitivity will be different at each spindle speed since the spindle motor efficiency changes with spindle speed.

3.2 Experiment Purpose

A magnetic brake and torque sensor system was used to characterize the FADAL EMC CNC milling machine and get an accurate estimation of cutting power based on spindle speed and the electrical power input into the spindle motor. A similar experiment has been done before [15], but because of the limitations of the previous experiment equipment, only spindle speeds less than 1800 RPM have been tested. To check whether the CNC machine performance has changed for the low range speeds (less than 2500
RPM) and explore its performance for the high range speeds (over 2500 RPM), new equipment and experiment procedures are needed.

3.3 Experiment Setup

The setup is shown in Figure 3.1. The magnetic brake, an AHB-6 from Magtrol, provides resistance torque that is proportional to the applied current. Torque sensor T22/20NM from HBM is used to measure the exact load torque provided by the magnetic brake while the spindle rotates at a specified speed. The LCI power sensor produces a signal which is proportional to the electrical input power $P_e$ to the spindle motor.

![Figure 3.1 - Motor Characterization Experiment Setup](image)

The experiment was performed at different spindle speeds, every 50 rpm from 200 to 700 rpm, then every 100 rpm from 800 to 2000 rpm and 2200, 2400 and 2500 rpm
for the low range. For the high range speeds, data was taken every 200 rpm from 2600 to 4000 rpm, including 3500 rpm. To prevent the brake from overheating, the input current was limited to a maximum of 1 amp for the low range speeds and 0.6 amps for the high range speeds. Readings were taken at evenly spaced current intervals, every 0.2 amps for the low range speeds and every 0.1 amps for the high range speeds. Readings were taken at 0 amps before and after each test sequence to assess mechanical friction and measuring system hysteresis. For each condition, actual torque provided by the brake and electrical power input to the motor are measured. Experiment procedures are described in Appendix A.

3.4 Experiment Results and Discussion

The results are shown in tabular form in Appendix B. The first four columns are spindle speed, current output from the BK power supply to the magnetic brake, voltage output from the torque sensor and measured torque respectively. The fifth column is the output mechanical power calculated from the measured torque and the spindle speed. The last column is the voltage output from the LCI power sensor.

Repeated test data is marked with an R in the table. For each spindle speed, data for zero input current was used to measure hysteresis and was not used to determine the power curve. Thus there are five data points used to calculate the spindle motor power sensor system sensitivity for each spindle speed in the low range and six data points for the high range.
At a given spindle speed, the relationship between the available cutting power and the electrical power input into the spindle motor in a cutting process is [15]:

\[ P_c = P_e \cdot \eta_e - P_f \]  \hspace{1cm} (3.1)

where \( P_c \) is the available cutting power which is actually used to machine the part, \( P_e \) is the electrical power input into the spindle motor, \( \eta_e \) is the motor efficiency and \( P_f \) is the power to overcome the mechanical friction in the motor and drive system. \( P_c + P_f \) can be regarded as the total mechanical power. \( \eta_e \) and \( P_f \) are assumed to be constant for a given spindle speed [15].

\( P_c \) can be expressed as:

\[ P_c = E_o \cdot K_p \]  \hspace{1cm} (3.2)

where \( E_o \) is output voltage from the LCI power sensor and \( K_p \) is the sensitivity of the LCI sensor in watt/volt.

Unfortunately, the sensitivity of the LCI power sensor \( K_p \) is not accurately known, which means the electrical power input to the spindle motor \( P_e \) is unknown. We substitute Equation 3.2 into Equation 3.1 and get:

\[ P_c = E_o \cdot K_p \cdot \eta_e - P_f = E_o \cdot K_s - P_f \]  \hspace{1cm} (3.3)
where $K_s$ equals $K_r \cdot \eta_c$, which is regarded as the spindle motor power sensor system sensitivity, or simply the motor-sensor system sensitivity.

For each spindle speed, a curve can be generated by plotting the available cutting power $P_c$ vs the LCI sensor voltage output $E_u$. We can see the curve is quite linear at every spindle speed. Figures 3.2 and 3.3 are the curves at 1500 and 3600 rpm respectively.

![Figure 3.2 - Available Cutting Power vs LCI Sensor Voltage Output at 1500 rpm](image.png)

$$y = 153.63x - 292.52$$
Figure 3.3 - Available Cutting Power vs LCI Sensor Voltage Output at 3600 rpm

From Equation 3.3, assuming the frictional losses are constant for a given spindle speed, we can see the plot of \( P_c \) vs \( E_n \) should be a line, and the slope of this line is \( K_s \).

Figures 3.2 and 3.3 confirm this. Based on Equation 3.3, when \( E_n \) is zero, \( P_c \) equals \( -P_f \), which corresponds to the intercept between the line and y axis in Figure 3.2 and 3.3.

When the spindle motor runs at a constant speed without cutting any material, \( P_c \) equals zero, the LCI sensor voltage output is called tare power voltage notified by \( E_t \). From Equation 3.3, when \( P_c \) equals zero, \( E_n \) equals to \( P_f / K_s \), which corresponds to the intercept between the line and x axis. After plotting figures similar to Figure 3.2 and 3.3 for all the different spindle speeds, we can get the slope of each line, which is the motor-
sensor system sensitivity at each spindle speed. Since the tests for spindle speed at 2500, 3000, 3500 and 4000 rpm are repeated once each, the sensitivity at these four different spindle speeds is gained through averaging. Table 3.1 shows the motor-sensor system sensitivity for each spindle speed. We can then plot the sensitivity versus the spindle speed as shown in Figure 3.4.

We find that the motor-sensor system sensitivity for the low range and the high range speeds seems to have different behavior, observable in Figure 3.4. That is because the CNC machine changes the transmission gears from the low range speeds to the high range speeds at a transition speed of 2500 rpm, resulting in the different trends of the motor-sensor system sensitivity for the low range and the high range speeds. Therefore different curves are needed to fit the sensitivity for the two speed ranges to better represent their behavior, which can be seen in Figure 3.5 and 3.6.

Table 3.1 - Motor-Sensor System Sensitivity ($K_s$) versus Spindle Speed ($\omega$)

<table>
<thead>
<tr>
<th>$\omega$ (rpm)</th>
<th>200</th>
<th>250</th>
<th>300</th>
<th>350</th>
<th>400</th>
<th>450</th>
<th>500</th>
<th>550</th>
<th>600</th>
<th>650</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_s$ (watt/volt)</td>
<td>144</td>
<td>145</td>
<td>143</td>
<td>145</td>
<td>146</td>
<td>149</td>
<td>150</td>
<td>147</td>
<td>147</td>
<td>150</td>
</tr>
<tr>
<td>$\omega$ (rpm)</td>
<td>700</td>
<td>750</td>
<td>800</td>
<td>900</td>
<td>1000</td>
<td>1100</td>
<td>1200</td>
<td>1300</td>
<td>1400</td>
<td>1500</td>
</tr>
<tr>
<td>$K_s$ (watt/volt)</td>
<td>149</td>
<td>148</td>
<td>150</td>
<td>148</td>
<td>153</td>
<td>153</td>
<td>153</td>
<td>152</td>
<td>151</td>
<td>154</td>
</tr>
<tr>
<td>$\omega$ (rpm)</td>
<td>1600</td>
<td>1700</td>
<td>1800</td>
<td>1900</td>
<td>2000</td>
<td>2200</td>
<td>2400</td>
<td>2500</td>
<td>2600</td>
<td>2800</td>
</tr>
<tr>
<td>$K_s$ (watt/volt)</td>
<td>152</td>
<td>152</td>
<td>151</td>
<td>152</td>
<td>152</td>
<td>151</td>
<td>149</td>
<td>147</td>
<td>139</td>
<td>139</td>
</tr>
<tr>
<td>$\omega$ (rpm)</td>
<td>3000</td>
<td>3200</td>
<td>3400</td>
<td>3500</td>
<td>3600</td>
<td>3800</td>
<td>4000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_s$ (watt/volt)</td>
<td>137</td>
<td>136</td>
<td>133</td>
<td>132</td>
<td>132</td>
<td>131</td>
<td>129</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 3.4 - Motor-Sensor System Sensitivity Plot

Figure 3.5 - Motor-Sensor System Sensitivity Curve for Low Range Speeds
Figure 3.6 - Motor-Sensor System Sensitivity Curve for High Range Speeds

Figure 3.7 and 3.8 are the residual plots for the fit of motor-sensor system sensitivity for the low range and high range speeds respectively. As we can see, the residuals are within 3 and 1.5 for each fit, which confirms that the quadratic curve and linear line fit the low range and high range data quite well respectively. Therefore the motor-sensor system sensitivity at any spindle speed from 200 to 4000 rpm can be estimated from the above curve fits.
Since there are residuals which can be regarded as the estimation error for the fit of motor-sensor system sensitivity, it is better to quantify how much the estimation error
would be, which can be found from the confidence interval and prediction interval of the fit in Figure 3.9 and 3.10 for the low range and high range speeds respectively.

The 95% confidence interval of the fit tells us the uncertainty in determining the mean of the motor-sensor system sensitivity for each spindle speed, while the 95% prediction interval of the fit tells us the distribution of the motor-sensor system sensitivity for each spindle speed. Thus we can quantify how much the variation would be using the corresponding fit to estimate the motor-sensor system sensitivity for each spindle speed.

\[ K_1 = -5.0593 \times 10^{-6} \omega^6 + 1.5238 \times 10^{-2} \omega + 141 \]  \hspace{1cm} (3.4)

where \( \omega \) is the spindle speed (rpm).

Figure 3.9 - Confidence and Prediction Interval for the Polynomial Fit of Motor-Sensor System Sensitivity for Low Range Speeds
The 95\% confidence interval of the fit is $K_s \pm 0.5155$ while the 95\% prediction interval of the fit is $K_s \pm 2.7761$.

![Figure 3.10 - Confidence and Prediction Interval for the Linear Fit of Motor-Sensor System Sensitivity for High Range Speeds](image)

For high range spindle speeds, the linear fit is:

$$K_s = -7.5094 \times 10^{-3} \times \omega + 159.29 \quad (3.5)$$

The 95\% confidence interval of the fit is $K_s \pm 0.6781$ while the 95\% prediction interval of the fit is $K_s \pm 2.1445$.

From Equation 3.3, at a given spindle speed, the change in $P_c$ is proportional to the change in $E_u$, which can be represented by Equation 3.6.

$$\Delta P_c = \Delta E_u \times K_s \quad (3.6)$$
where $\Delta P_c$ and $\Delta E_o$ are the change in $P_c$ and $E_o$, respectively. Now that we have the motor-sensor system sensitivity $K$, for any spindle speed, $\Delta P_c$ can be simply calculated with Equation 3.6. During the actual cutting test, the tare power voltage $E_o$ is measured when $P_c$ is zero. After measuring the LCI sensor voltage output $E_o$ for any case which is machining material, the actual cutting power can then be calculated using Equation 3.7.

$$P_c = (E_o - E_t) \times K,$$

### 3.5 Summary

This chapter describes the spindle motor characterization experiment to calibrate the motor-sensor system sensitivity at each spindle speed. As can be seen, the motor-sensor system sensitivity is different at each spindle speed since the spindle motor efficiency changes with spindle speed. The obtained sensitivity can then be used to estimate the cutting power for milling force model calibration.
CHAPTER 4

CUTTING TEST DESIGN

4.1 Introduction

This chapter introduces the cutting test design for force model calibration. The choices of cutting process variables such as spindle speed, radial immersion, axial depth of cut, tool geometry and workpiece material are included. The data recording system is briefly introduced as well.

To minimize the dynamic effects of both the Kistler dynamometer and the Smart Tool on force measurements and tool vibration, we designed cutting tests at a relatively low spindle speed of 600 rpm. We also designed cutting tests at a high spindle speed of 3000 rpm for comparison.

4.2 Cutting Test Design

As mentioned in Chapter 2, the dynamic effects of the Kistler force dynamometer limit its frequency range to around 200 Hz. The Smart Tool frequency response is unknown, but it is found to have a natural frequency of approximately 650 Hz.

In order to minimize the dynamic effects of both sensors on force measurement, we designed cutting tests at a relatively low spindle speed of 600 rpm. For a one tooth cutter, this gives a periodic signal with a fundamental frequency of 10 Hz, well below the
bandwidth of both dynamometers. We also designed and conducted cutting tests at a high spindle speed of 3000 rpm for comparison.

Currently, the Smart Tool is only capable of measuring either tangential force or radial force at a given time, thus each experiment had to be performed twice in order to collect both radial and tangential components for calibration. For the results of this calibration to be accurate, it is required that cut-to-cut variability remains small. In the rest of this thesis, (T) denotes the experiment that was conducted with the Smart Tool measuring tangential force while (R) denotes the experiment that was conducted with the Smart Tool measuring radial force.

Up milling cutting tests are performed and repeated once at both 600 and 3000 rpm using a single tooth cutter to eliminate the effect of tool runout and to lower the tooth passing frequency to 10 and 50 Hz respectively. The diameter of the cutting tool is 19.05 mm and the helix angle is 14.73 degrees. The insert of the cutting tool is a Sandvik R390-11 T3 08E-NL H13A. The workpiece material is aluminum 6061. The axial depth of cut is 3.175 mm (0.125 inch). Table 4.1 and 4.2 show the feedrates for the cutting tests at 600 and 3000 rpm respectively. The four feedrates for each radial immersion are chosen to make the average chip thickness 0.0254, 0.0508, 0.0762 and 0.1016 mm (0.001, 0.002, 0.003 and 0.004 inches) respectively.
Table 4.1 - Feedrate Design for 600 rpm Cutting Test

<table>
<thead>
<tr>
<th>Feedrate (mm/sec)</th>
<th>Quarter Immersion</th>
<th>Half Immersion</th>
<th>Three Quarter Immersion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedrate 1</td>
<td>0.5321</td>
<td>0.3988</td>
<td>0.3548</td>
</tr>
<tr>
<td>Feedrate 2</td>
<td>1.0638</td>
<td>0.7980</td>
<td>0.7095</td>
</tr>
<tr>
<td>Feedrate 3</td>
<td>1.5960</td>
<td>1.1968</td>
<td>1.0638</td>
</tr>
<tr>
<td>Feedrate 4</td>
<td>2.1281</td>
<td>1.5960</td>
<td>1.4186</td>
</tr>
</tbody>
</table>

Table 4.2 - Feedrate Design for 3000 rpm Cutting Test

<table>
<thead>
<tr>
<th>Feedrate (mm/sec)</th>
<th>Quarter Immersion</th>
<th>Half Immersion</th>
<th>Three Quarter Immersion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedrate 1</td>
<td>2.6598</td>
<td>1.9947</td>
<td>1.7733</td>
</tr>
<tr>
<td>Feedrate 2</td>
<td>5.3196</td>
<td>3.9899</td>
<td>3.5467</td>
</tr>
<tr>
<td>Feedrate 3</td>
<td>7.9798</td>
<td>5.9857</td>
<td>5.3196</td>
</tr>
<tr>
<td>Feedrate 4</td>
<td>10.6396</td>
<td>7.9798</td>
<td>7.0930</td>
</tr>
</tbody>
</table>

The average chip thickness for up milling can be expressed as [11]:

\[
h_a = -c \frac{\cos \phi_{r_z} - \cos \phi_{s_z}}{\phi_{r_z} - \phi_{s_z}}
\]  

(4.1)

For each radial immersion cutting test, the feedrate changes in steps from feedrate 1 to feedrate 4 as the cutting tool moves in the feed direction, as shown in Figure 4.1.
During the cutting processes, the instantaneous cutting forces $F_x$ and $F_y$ are measured by the Kistler dynamometer having an anti-aliasing filter with a cut-off frequency at 2.2 KHz and recorded by a computer through a data acquisition board with the sampling frequency of 7200 Hz and 18000 Hz for the 600 rpm and 3000 rpm cutting tests respectively. For cutting tests at 600 rpm, 720 samples are taken for each tool revolution while for cutting tests at 3000 rpm, 360 samples are taken for each tool revolution. Data measured by the LCI power sensor is recorded by the same board at the same sampling rate as the Kistler dynamometer data.

The Smart Tool has a fixed sampling frequency of 10.24 kHz for all cutting tests and has an anti-aliasing filter with a cut-off frequency at 2.84 kHz. Instantaneous tangential or radial forces measured by the Smart Tool are transmitted through Bluetooth and recorded by a separate computer.
4.3 Summary

In this chapter, the cutting test design for force model calibration is presented. The choices of spindle speed, radial immersion, axial depth of cut, tool geometry and workpiece material are given and a brief introduction of the data recording system is included.

In order to minimize the dynamic effects of both sensors on force measurement, cutting tests are performed at a relatively low spindle speed of 600 rpm. For a one tooth cutter, this gives a periodic signal with a fundamental frequency of 10 Hz, well below the bandwidth of both dynamometers. We also designed cutting tests at a high spindle speed of 3000 rpm for comparison.
CHAPTER 5

FORCE MODEL CALIBRATION METHODS

5.1 Introduction

As mentioned in Chapter 2, five different calibration methods are introduced and compared in this research. They are based on spindle motor power, Kistler average force and force profile, and Smart Tool average force and force profile. This chapter describes each calibration method in detail.

5.2 Spindle Motor Power

Based on previous research, we have the following relationship between the average cutting power and the cutting geometry [14]:

\[ P_c = K_v \cdot \dot{Q} + K_w \cdot \dot{A}_r. \] (5.1)

where \( P_c, \dot{Q} \) and \( \dot{A}_r \) are average cutting power, volumetric removal rate and contact area rate respectively.

The cutting power is related to the spindle motor power through:

\[ P_c = (E_o - E_i) \cdot K_s. \] (5.2)

Please refer to Chapter 3 for detailed derivation of Equation 5.2 which was presented as Equation 3.7 in Section 3.4.
Usually, we rotate the spindle at a desired speed for about 10 – 15 minutes before measuring tare power voltage $E_r$. $E_o$ and $E_s$ can be easily measured from the LCI power sensor. As long as we have the motor-sensor system sensitivity $K_s$, which can be found through the experiments described in Chapter 3, we can get $P_c$ from Equation 5.2. The volumetric removal rate and contact area rate for each cutting test can be found from the cutting geometry [5]. Equation 5.1 is written once for each test and then combined in matrix form:

$$[P_c] = \begin{bmatrix} \dot{Q} & \dot{A}_r \end{bmatrix} \begin{bmatrix} K_{c_r} \\ K_{c_n} \end{bmatrix} = [G][K_s]$$

(5.3)

where the $G$ matrix is defined by the cutting geometry.

Least square regression can be applied to the above equation to obtain the tangential cutting coefficients.

$$K_s = (G^T G)^{-1} G^T P_c$$

(5.4)

After we get the tangential cutting coefficients, a ratio method can be applied to get the radial cutting coefficients $K_n$ and $K_{c_n}$ [17]. Specifically, the ratios of radial to tangential cutting coefficients can be found from the four cutting coefficients calibrated from the Kistler average force based method. Then those ratios can be applied to the tangential coefficients calibrated from the spindle motor power to get the radial coefficients.
5.3 Kistler Reaction Force

The Kistler dynamometer 9257B is used in this research to measure the reaction force between the workpiece and the cutting tool in both X and Y directions.

5.3.1 Force Profile Method

Based on the force model described in Chapter 2, a number of $F_x$ and $F_y$ forces, with known cutting geometry values and unknown edge locating angle at each instant the forces are measured, can be combined in the following matrix form:

$$[F] = [M][K]$$  \hspace{1cm} (5.5)

where $[F] = [F_x, F_y, \ldots]$ is the matrix of forces, $[K] = [K_{rc}, K_{ec}, K_{re}, K_{re}]$ is the matrix of cutting coefficients, and $[M]$ is the geometric matrix consisting of the remaining terms in Equation 2.7 with the four cutting coefficients removed. An example $M$ matrix is:

$$[M] = \begin{bmatrix}
-\frac{c}{4k_\rho} \cos 2\phi_e^* & \frac{1}{k_\rho} \sin \phi_e^* & \frac{c}{4k_\rho} (2\phi - \sin 2\phi)^* & -\frac{1}{k_\rho} \cos \phi_e^* \\
\vdots & \vdots & \vdots & \vdots \\
-\frac{c}{4k_\rho} (2\phi - \sin 2\phi)^* & \frac{1}{k_\rho} \cos \phi_e^* & -\frac{c}{4k_\rho} \cos 2\phi_e^* & \frac{1}{k_\rho} \sin \phi_e^* \\
\end{bmatrix}$$  \hspace{1cm} (5.6)
where $c$ is the feed per tooth (mm/tooth), $\phi_1$ and $\phi_2$ are the edge locating angle for the lower and upper axial engagement limits of the in-cut portion of the flute and they have the following relationship:

$$\phi_2 = \phi_1 - k_\beta \cdot a$$

where $a$ is the axial depth of cut. Please refer to Section 2.1 for the definition of $k_\beta$.

A least squares estimation can be applied to Equation 5.5 to calculate the cutting coefficients $K_{tc}$, $K_{te}$, $K_{rc}$ and $K_{re}$:

$$
\begin{bmatrix}
K_{rc} \\
K_{re} \\
K_{rc} \\
K_{re}
\end{bmatrix} = (M^T M)^{-1} M^T F
$$

To use a cutting force profile and least squares regression to calibrate the cutting coefficients, we need to average a number of cycles of cutting force to get one average profile, with less noise, to form the force matrix $F$ in Equation 5.8. We also need to know the geometric matrix $M$, consisting of the known feed per tooth, the diameter and helix angle of the cutting tool, and the unknown edge locating angles. These angles are for the lower and upper limit of the in-cut portion of the flute at each instant the force is measured.

To get the edge locating angles, we use a Hall element sensor mounted on the housing of the spindle of our CNC machine. The sensor outputs a pulse when the spindle just reaches its home position. This provides a once per revolution "tick signal" that can be used to determine edge locating angles. As long as we can get one clean cycle of
cutting force and the corresponding geometric matrix, then we can easily implement the least squares regression (Equation 5.8) to get the cutting coefficients.

**Aligning and Averaging Different Cycles of Force**

Figures 5.1 and 5.2 show the profile of 20 cycles of instantaneous force $F_x$ and $F_y$ measured by the Kistler dynamometer for one cutting case (600 rpm, quarter immersion, feedrate 1 (T)) respectively. We find both $F_x$ and $F_y$ vary some in amplitude and have noticeable noise.

![Figure 5.1 - 20 Cycles of $F_x$, 600 rpm, Quarter Immersion and Feedrate 1 (T)](image-url)
Figures 5.3 and 5.4 show the FFT results of the cutting force presented in Figures 5.1 and 5.2 respectively. The FFT results confirm that most frequency components of the cutting force lie within the working bandwidth of the Kistler and it is possible to use the force data directly without any filtering.

Figure 5.3 - FFT of $F_y$, 600 rpm, Quarter Immersion and Feedrate 1 (T)

Figure 5.2 - 20 Cycles of $F_y$, 600 rpm, Quarter Immersion and Feedrate 1 (T)
In order to get a clean force profile which can be used in the calibration of the cutting coefficients, we align 20 selected cycles of $F_x$ and $F_y$ and average them to get one cycle of $F_x$ and $F_y$. Figures 5.5 and 5.6 show the unshifted 20 cycles of $F_x$ and $F_y$. Because of the stochastic nature of cutting and the fact that the spindle speed of the CNC machine may vary during the cutting test (open-loop induction motor), the unshifted 20 cycles of $F_x$ and $F_y$ are not perfectly aligned with each other. To correctly align the 20 cycles of force, the first cycle is selected as the reference and each one of the remaining cycles is compared to the first cycle and shifted back and forth based on the cross-correlation between itself and the first cycle. Figures 5.7 and 5.8 show the shifted 20 cycles of $F_x$ and $F_y$. After being aligned, the 20 cycles of force are then averaged to get one cycle of force, as shown in Figures 5.9 and 5.10.
Figure 5.5 - Unshifted $F_x$, 600 rpm, Quarter Immersion and Feedrate 1 (T)

Figure 5.6 - Unshifted $F_y$, 600 rpm, Quarter Immersion and Feedrate 1 (T)
Figure 5.7 - Shifted $F_x$, 600 rpm, Quarter Immersion and Feedrate 1 (T)

Figure 5.8 - Shifted $F_y$, 600 rpm, Quarter Immersion and Feedrate 1 (T)
To implement the least squares regression to get the cutting coefficients, we need to know the elements of the Geometric matrix described in Equation 5.6. The elements depend on the known feed per tooth, the helix angle and diameter of the cutting tool, and
During the periods when the cutting tooth begins to enter and exit from the cutting region, the cutting tool is not fully engaged, so we do not use that force data in the calibration calculations. This section of force is represented by the circles in Figure 5.11. Typically, we use the force data for calibration when the cutting tooth is fully engaged in the desired axial depth of cut. For example, we use the range of [10 50], [10 80] and [10 110] degrees of the reference locating angle to do the calibration for quarter, half and three quarter immersion cutting tests respectively.

The procedure for calculating the coefficients starts by populating the M matrix as defined in Equations 5.5 - 5.7. With two samples per degree the M matrix will be 160x4 for the 40 degrees of interest during a 600 rpm quarter immersion cut (both x and y forces times 2 samples per degree times 40 degrees). Then we use the least squares regression expressed in Equation 5.8 to get the cutting coefficients.
The force profile based cutting coefficients for the cutting test of 600 rpm, quarter immersion and feedrate 1 (T) are: $K_{tc}=1119.3$ N/mm$^2$, $K_{te}=9.9$ N/mm, and $K_{rc}=398.0$ N/mm$^2$, $K_{re}=10.3$ N/mm.

![Figure 5.11 - Cutting Force Profile and Tick Signal, 600 rpm, Quarter Immersion and Feedrate 1 (T)](image)

5.3.2 Average Force Method

Average cutting forces in the x and y direction for up milling can be expressed as Equation 5.9 and 5.10 respectively. In the equations, N is the number of teeth, $a$ is the axial depth of cut, c is the feed per tooth, $\phi_e$ is the entry angle and $\phi_{ex}$ is the exit angle [6, 11].

$$\bar{F}_x = \frac{Nac}{8\pi} \left[ K_n (\cos 2\phi_{ex} - \cos 2\phi_e) - K_n [2\phi_{ex} - 2\phi_e - (\sin 2\phi_{ex} - \sin 2\phi_e)] \right]$$

$$+ \frac{Na}{2\pi} \left[ - K_n [\sin \phi_{ex} - \sin \phi_e] + K_n [\cos \phi_{ex} - \cos \phi_e] \right]$$

(5.9)
\[
\overline{F}_y = \left\{ \begin{array}{c}
\frac{Nac}{8\pi} \left[ K_n (2\phi_r - 2\phi_v - (\sin 2\phi_r - \sin 2\phi_v)) + K_n [\cos 2\phi_r - \cos 2\phi_v] \right] \\
- \frac{Na}{2\pi} \left[ K_n (\cos \phi_r - \cos \phi_v) + K_n (\sin \phi_r - \sin \phi_v) \right]
\end{array} \right\}
\]

(5.10)

Equation 5.9 and 5.10 can be combined into a matrix form as seen in Equation 5.11, where \( K \) contains the model coefficients and \( G \) depends on the cutting geometry.

Refer to [6] for an example of a \( G \) matrix.

\[
\overline{F} = GK
\]

(5.11)

Similarly, least squares estimation can be applied to Equation 5.11 to calculate the four cutting coefficients \( K_{tc}, K_{te}, K_{rc}, \) and \( K_{re} \), in

\[
\begin{bmatrix}
K_n \\
K_{\phi} \\
K_r \\
K_{\phi r}
\end{bmatrix}
= (G^T G)^{-1} G^T \overline{F}
\]

(5.12)

5.4 Smart Tool Tangential and Radial Force

The Smart Tool is used to measure tangential and radial forces during cutting.

Two calibration methods using the Smart Tool, force profile and average force, are now described.

5.4.1 Force Profile Method

Due to the design of the Smart Tool [16] and the small axial depth of cut of the designed cutting tests, we ignore the 14.73 degree helix angle of the cutting tool and
assume that it has a single straight cutting flute. The instantaneous tangential and radial force at each edge locating angle \( \phi \) can then be expressed as:

\[
F_t = [K_n \cdot h(\phi) + K_{ic}] \cdot a
\]  \hspace{1cm} (5.13)

\[
F_r = [K_n \cdot h(\phi) + K_{ic}] \cdot a
\]  \hspace{1cm} (5.14)

where \( h(\phi) \) is the instantaneous chip thickness expressed in Equation 2.3.

Equation 5.13 can be rewritten as:

\[
F_t / a = K_n \cdot h(\phi) + K_{ic}
\]  \hspace{1cm} (5.15)

If we plot \( F_t / a \) against instantaneous chip thickness \( h(\phi) \) for one tool rotation, we can fit a line to the data. The slope of the fitted line would be \( K_n \) while the intercept between the fitting line and the Y axis would be \( K_{ic} \).

Similar to the Kistler force profile based method, we also align and average 20 cycles of tangential force to get one clean cycle to calibrate cutting coefficients. Figure 5.12 shows the chosen 20 cycles of tangential force for the cutting test of 600 rpm, quarter immersion and feedrate 1. Figure 5.13 shows the FFT result of the tangential force, which tells us that most frequency components of the tangential force lie below 200 Hz, well below the natural frequency of the Smart Tool which is around 650 Hz as mentioned in Chapter 2. Therefore it is possible to use the tangential force directly without any filtering to calibrate the tangential coefficients. Figures 5.14 and 5.15 show
the unshifted and shifted 20 cycles of the tangential force respectively. Figure 5.16 shows
the averaged one cycle of the tangential force.

Figure 5.12 - 20 Cycles of $F_t$, 600 rpm, Quarter Immersion and Feedrate 1

Figure 5.13 - FFT of $F_t$, 600 rpm, Quarter Immersion and Feedrate 1
Figure 5.14 - Unshifted $F_t$, 600 rpm, Quarter Immersion and Feedrate 1

Figure 5.15 - Shifted $F_t$, 600 rpm, Quarter Immersion and Feedrate 1
Because the forces measured by the Smart Tool are recorded by a separate computer, the previously mentioned “tick signal” is not available. So we don’t really know the edge locating angles at each instant the tangential or radial forces are sampled, which means the exact instantaneous chip thickness corresponding to each force data is unknown. However, by looking at the tangential force profile shown in Figure 5.16, we can choose the data point which has a force value bigger than but closest to zero as the instant when the cutting tool just begins to engage in cutting, as noted by “Cutting Start Point” in Figure 5.16. For up milling, this start point corresponds to the edge locating angle of zero.

During periods when the cutting tooth begins to enter and exit from the cutting region, the cutting tool is not fully engaged so the force data in the very beginning or the very end of the tooth engagement is not used. This is represented by the circles in Figure 5.16. Typically, we use the force data when the cutting tooth is fully engaged in the
desired axial depth of cut to do the calibration. As mentioned in the Kistler force profile based method, we use the range of [10 50], [10 80] and [10 110] degrees of the reference locating angle to do the calibration for quarter, half and three quarter immersion cutting tests respectively.

\[ y = 1015.6 x + 15.671 \]

Figure 5.17 shows \( F_t/a \) vs instantaneous chip thickness for the cutting test of 600 rpm, quarter immersion and feedrate 1 with the tangential coefficients calibration result: \( K_{tc} = 1012.4 \text{ N/mm}^2 \) and \( K_{te} = 16.0 \text{ N/mm} \). As can be seen, the experiment data of \( F_t/a \) vs instantaneous chip thickness is not a perfect line and there exists waviness especially when the chip thickness is small. Tool vibration occurs in the 600 rpm cutting test and this affects the instantaneous chip thickness, resulting in waviness. Because the tool vibration is small, it has less effect with increasing chip thickness. That’s why the waviness fades away with increasing chip thickness.
Similarly, we can get radial coefficients from radial force data using exactly the same method. For example, we get the following radial coefficients for the cutting test of 600 rpm, quarter immersion and feedrate 1: \(K_{rc} = 293.9437 \text{ N/mm}^2\) and \(K_{re} = 11.3970 \text{ N/mm}\).

### 5.4.2 Average Force Method

We can formulate average tangential and radial forces by substituting Equations 5.13 and 5.14 into the following integrations.

\[
\overline{F_t} = \frac{N}{2\pi} \int_{\phi} F_t d\phi \\
\overline{F_r} = \frac{N}{2\pi} \int_{\phi} F_r d\phi
\]  

(5.16)

(5.17)

where \(N\) notifies the number of cutting tooth.

The average tangential and radial forces for up milling can then be expressed as:

\[
\overline{F_i} = -\frac{Nac}{2\pi} K_n (\cos 2\phi_v - \cos 2\phi_u) + \frac{Na}{2\pi} K_n (\phi_v - \phi_u)
\]

(5.18)

\[
\overline{F_r} = -\frac{Nac}{2\pi} K_e (\cos 2\phi_v - \cos 2\phi_u) + \frac{Na}{2\pi} K_e (\phi_v - \phi_u)
\]

(5.19)

Similar to the Kistler average force based calibration method, the above equations can be combined into matrix form and a least squares regression can be applied to them to obtain the tangential and radial coefficients respectively.
5.5 Summary

Five different calibration methods are described in detail in this chapter. A least squares regression is applied to all the methods to calibrate the cutting coefficients. The spindle motor power based method can only provide tangential coefficients, so an assumed ratio of radial to tangential coefficients could be utilized to find the radial coefficients. As for the other four calibration methods, all the four cutting coefficients can be obtained.
CHAPTER 6

CALIBRATION AND SIMULATION RESULTS AND COMPARISON OF METHODS

6.1 Introduction

Cutting coefficients calibration results of the five different methods are shown and compared in this chapter. Then the simulated resultant cutting force using the calibrated coefficients from each method is compared to the forces as measured by the Kistler dynamometer. The Kistler is widely used in research due to its well known accuracy. Discussion and comparison of the five different calibration methods in terms of cost, efficiency, compliance, accuracy, repeatability and applicability is also presented in this chapter.

We show all the calibration and simulation results in bar plots in this chapter. The results can also be found in tabular form in Appendix C and D. As mentioned previously in Chapter 4, since the Smart Tool is only capable of measuring either tangential force or radial force at a given time, the experiments had to be performed twice in order to collect both radial and tangential components for calibration. In the rest of this thesis, (T) denotes the experiment that was conducted with the Smart Tool measuring tangential force while (R) denotes the experiment that was conducted with the Smart Tool measuring radial force.
6.2 Calibration Results

Figure 6.1 shows the average force and spindle motor power based cutting coefficients for 600 rpm cutting tests. Figures 6.2 and 6.3 show the Kistler force profile based and Smart Tool force profile based cutting coefficients for 600 rpm cutting tests respectively. Figure 6.4 shows the average force and spindle motor power based cutting coefficients for 3000 rpm cutting tests. Figures 6.5 and 6.6 show the Kistler force profile based and Smart Tool force profile based cutting coefficients for 3000 rpm cutting tests respectively.

Figure 6.1 - Average Force and Spindle Motor Power Based Calibration Results for 600 rpm Cutting Tests
Figure 6.2 - Kistler Force Profile Based Calibration Results for 600 rpm Cutting Tests
Figure 6.3 – Smart Tool Force Profile Based Calibration Results for 600 rpm Cutting Tests
Figure 6.4 - Average Force and Spindle Motor Power Based Calibration Results for 3000 rpm Cutting Tests
Figure 6.5 - Kistler Force Profile Based Calibration Results for 3000 rpm Cutting Tests
As mentioned in Chapter 5, in order to use the spindle motor power based calibration method, the ratios of radial to tangential cutting coefficients are necessary. We applied the following ratios found from the six sets of the four cutting coefficients calibrated from the Kistler average force based method to get the radial coefficients for the spindle motor power based method.
Table 6.1 - Mean of $K_{rc}/K_{tc}$ and $K_{re}/K_{te}$

<table>
<thead>
<tr>
<th></th>
<th>Mean $K_{rc}/K_{tc}$</th>
<th>Mean $K_{re}/K_{tc}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>600 rpm</td>
<td>0.3686</td>
<td>0.5623</td>
</tr>
<tr>
<td>3000 rpm</td>
<td>0.3959</td>
<td>0.6301</td>
</tr>
</tbody>
</table>

It would be better to get the ratios for each tool-workpiece pair without considering any other cutting conditions such as spindle speed, radial immersion and axial depth of cut. However, note that coolant was used in the 600 rpm cutting tests but not in the 3000 rpm cutting tests, thus it may have an effect on the ratios. Therefore we use the ratios obtained from the 600 rpm and 3000 rpm cutting tests separately.

Also note that the Smart Tool can only measure tangential or radial force at a given time, thus only tangential or radial coefficients can be obtained for both Smart Tool average force based and force profile based methods for a given cutting test.

From all the calibration results shown in Figures 6.1 – 6.6 or Tables C.1 – C.36, we can draw the following conclusions:

- The Kistler average force based calibration method shows consistent results of all the four cutting coefficients for the same cutting geometry, with typical values within 5%, which can be assessed through comparing the cutting coefficients from the Kistler Average Force (T) and (R) from Figures 6.1 and 6.4. We can draw the same conclusion for the Kistler force profile based and spindle motor power based calibration methods. This indicates that these three calibration
methods can provide repeatable and consistent calibration results. We are not as certain about the consistency of results obtained using the Smart Tool average force and force profile based calibration methods due to the limited experiments we have conducted. This should be investigated in the future.

- The Kistler average force based, the Smart Tool average force based and the spindle motor power based methods provide similar results for $K_{tc}$ for the same cutting geometry, with an error within 10%, which can be assessed from Figures 6.1 and 6.4.

- The “see-saw effect”, which means higher (or lower) shearing coefficients ($K_{tc}$ or $K_{re}$) are offset by lower (or higher) edge coefficients ($K_{te}$ or $K_{re}$), has been found consistently among almost all the calibration results. This can be verified by comparing the cutting coefficients obtained from different methods but for the same cutting condition, or from the same force profile based method but for different feedrates. We believe the “see-saw effect” to be an artifact of the regression being applied to the cutting coefficients which are highly cross correlated [6].

- The Kistler force profile based calibration method provides quite different sets of cutting coefficients between feedrate 1 and other feedrates for all the three different radial immersion cutting tests, especially for quarter and half immersion cutting tests, indicating that chip thicknesses of small value used in calibration will have an effect on estimating cutting coefficients. The same conclusion can be
drawn for the Smart Tool force profile based calibration method. It tells us that we need to be careful about choosing which range of chip thickness is used for force profile based calibration. This is a topic for future investigation.

6.3 Simulation Results

Accurate estimation of the peak resultant cutting force is very important in process planning in order to avoid tool breakage and excessive deflection. We evaluate the accuracy by comparing the estimated peak resultant cutting forces to those measured from the Kistler dynamometer. The resultant cutting force is easily calculated from the X and Y components:

\[ F_{\text{r}} = \sqrt{F_x^2 + F_y^2} \]  

(6.1)

The cutting coefficients obtained from each method can be used to simulate the resultant cutting force. Considering the effect of helix angle of the cutting tool, we need to divide the in-cut portion of the cutting flute into small slices and add up all the cutting forces contributed from each differential slices using Equations 2.7 - 2.11 described in Chapter 2.

The simulated resultant cutting force is compared to the averaged measured force profile for one tool revolution. Figures 6.7, 6.8 and 6.9 show the comparison between the simulated resultant cutting forces and the measured ones for cases of 600 rpm, quarter immersion and feedrate 1 (T), half immersion and feedrate 2 (T) and three quarter immersion and feedrate 3 (T) respectively. Figures 6.10, 6.11 and 6.12 show the comparison between the simulated and measured resultant cutting forces for cases of
3000 rpm, quarter immersion and feedrate 1 (T), half immersion and feedrate 2 (T) and three quarter immersion and feedrate 3 (T) respectively. In all these figures, Simulated 1, 2, 3, 4 and 5 denote simulation using the corresponding cutting coefficients obtained from the methods based on: 1. Kistler average force, 2. Smart Tool average force, 3. spindle motor power, 4. Kistler force profile and 5. Smart Tool force profile.

Figure 6.7 - Resultant Force Simulation for 600 rpm, Quarter Immersion and Feedrate 1 (T)
Figure 6.8 - Resultant Force Simulation for 600 rpm, Half Immersion and Feedrate 2 (T)

Figure 6.9 - Resultant Force Simulation for 600 rpm, Three Quarter Immersion and Feedrate 3 (T)
Figure 6.10 - Resultant Force Simulation for 3000 rpm, Quarter Immersion and Feedrate 1 (T)

Figure 6.11 - Resultant Force Simulation for 3000 rpm, Half Immersion and Feedrate 2 (T)
The relative error of the peak force can be expressed as:

\[ RE_p = \frac{F_p - F_{pm}}{F_{pm}} \times 100\% \]  \hspace{1cm} (6.2)

where \( RE_p \) is the relative error between the peak of the simulated resultant force and that of the measured one, \( F_p \) is the peak of the simulated resultant force and \( F_{pm} \) is the peak of the measured one.

Figures 6.13 and 6.14 show the results of \( RE_p \) for all the calibration methods for the cutting tests of 600 and 3000 rpm respectively.
Figure 6.13 – $RE_p$ for 600 rpm Cutting Tests
Figure 6.14 – $R_{Ep}$ for 3000 rpm Cutting Tests
As can be seen from Figures 6.13 and 6.14 (or all the simulation results shown in Appendix D), we can draw the following conclusions:

For quarter and three quarter immersion (for both 600 and 3000 rpm) cutting tests, almost all the simulated peak resultant forces of the five methods are less than the measured. For half immersion (for both 600 and 3000 rpm) cutting tests, the simulated peak resultant forces of the Kistler force profile and Smart Tool force profile methods are larger than the measured, while the simulated peak resultant forces of the other three methods are less than the measured.

The absolute value of the relative error between the simulated and measured peak resultant force is usually less than 10% for all the calibration methods except the spindle motor power based method. This is most evident for 600 rpm cutting tests because the low spindle speed causes less tool vibration and the Kistler dynamometer’s dynamic effects can be neglected. This accuracy level would be suitable for process planning and monitoring. Since the same conditions are used for calibration and force comparison, we would expect larger errors for cuts with different spindle speeds and cut geometries.

The spindle motor power based method provides a simulation error of over 10% for almost all the quarter and three quarter immersion cutting tests, and even over 25% for some cases. Two possible sources could account for this: 1. the estimated cutting power from the measured spindle motor power used for calibration may not be accurate; 2. the assigned ratios of radial to tangential coefficients may not be accurate. The true reason is still under investigation and would be part of the future work. However, the spindle motor power based calibration method can provide good estimation for peak
resultant forces for half immersion cutting tests, with a typical error within 5% of the measured ones.

The force profile (both Kistler and Smart Tool) based calibration methods can provide better estimation of the peak resultant force than the average force (both Kistler and Smart Tool) based calibration methods for quarter immersion cutting tests while the latter ones can provide better estimation of the peak resultant force for half immersion cutting tests. They provide comparable simulation results for three quarter immersion cutting tests.

6.4 Comparison of Methods

The five different calibration methods are compared to each other in terms of the following aspects: cost, efficiency, compliance, accuracy, repeatability and applicability.

a. Cost

<table>
<thead>
<tr>
<th>Kistler Dynamometer</th>
<th>Smart Tool</th>
<th>LCI Power Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$35,000</td>
<td>$2000 - 7000</td>
<td>$650</td>
</tr>
</tbody>
</table>

As can be seen in Table 6.2, the LCI power sensor costs the least while the Kistler dynamometer is the most expensive. However, both the Kistler dynamometer and the LCI power sensor are commercially available products while the Smart Tool is custom-designed and not commercially available. The estimated cost of the Smart Tool includes
the strain gages, data transmission board, battery, charging circuits and other electronics, the shrouding as well as the fabricating and calibrating cost.

b. Efficiency

The Kistler and Smart Tool average force calibration methods and the spindle motor power calibration method are more efficient than the Kistler and Smart Tool force profile calibration methods if implemented on-line because the former three calibration methods don’t need to find the correct edge locating angle of the cutting tool and their associated geometric matrices are much simpler and easier to handle.

c. Compliance

Although the Kistler dynamometer is really stiff, it is invasive to the CNC machine. It has a natural frequency around 1000 Hz with a workpiece attached to its top, which could affect the measurement. The LCI power sensor is non-invasive. The Smart Tool is significantly less stiff than the Kistler dynamometer, however, it does not add any additional compliance to the spindle system. The compliance does compromise its ability to obtain accurate measurement, particularly since its natural frequency is around 650 Hz which is less than the Kistler dynamometer.

d. Accuracy

The accuracy of the five different calibration methods can be assessed from the relative error of the simulation results shown in Figures 6.13 and 6.14 or in Appendix D. As can be seen, the relative error between the simulated and measured peak resultant
The spindle motor power based method provides a simulation error of over 10% for almost all the quarter and three quarter immersion cutting tests, and even over 25% for some cases. Two possible sources could account for this: 1. the estimated cutting power from the measured spindle motor power used for calibration may not be accurate; 2. the assigned ratios of radial to tangential coefficients may not be accurate. The true reason is still under investigation and would be part of the future work. However, the spindle motor power based method can provide good estimation for peak resultant forces for half immersion cutting tests, with a typical error within 5%.

For the 3000 rpm cutting tests, although there are noticeable and significant tool vibrations and dynamic effects of the force dynamometers, all the five calibration methods can still provide good estimation of the peak resultant forces, especially for half immersion cutting tests, with a typical error within 10%.

The force profile (both Kistler and Smart Tool) based calibration methods can provide better estimation of the peak resultant force than the average force (both Kistler and Smart Tool) based calibration methods for quarter immersion cutting tests while the latter ones can provide better estimation of the peak resultant force for half immersion
cutting tests. They provide comparable simulation results for three quarter immersion cutting tests.

e. Repeatability

Repeatability means how repeatable the calibration results of a method are for the same cutting geometry. Repeatability is an important factor because a calibration method should provide the same calibration results for the same tool - workpiece pair and the same cutting geometry if tool wear is negligible. Otherwise the calibration method has little practicality. As addressed previously in Calibration Results, the Kistler average force based calibration method shows close calibration results for all four cutting coefficients for the same cutting geometry, with a typical error within 5%. We can draw the same conclusion for the Kistler force profile based and spindle motor power based calibration methods. This indicates that these three calibration methods can provide repeatable and consistent calibration results. We are not sure how repeatable the calibration results of the Smart Tool average force and force profile based calibration methods are for the same cutting condition because of the limited experiments we have conducted. This should be investigated further in future.

f. Applicability

As discussed before, due to the high cost, workpiece mounting limitations and the intrusive nature, the Kistler dynamometer is not a good choice for the shop floor environment, while the power sensor can be easily implemented and used in shop floor due to its relatively low cost and non-intrusive property. However, only tangential cutting
coefficients can be obtained from the spindle motor power based method. As for the Smart Tool, although it is inexpensive, it is custom-designed and accurate calibration is needed before its application. In addition, the Smart Tool is currently limited to one cutting tooth. More importantly, a Smart Tool is needed for each cutting tool holder whereas a Kistler dynamometer and a LCI power sensor are only one per machine.

The Kistler and Smart Tool average force methods and the spindle motor power method need at least two different cutting conditions to generate two different average chip thicknesses to realize the calibration. Thus, one cannot get the cutting coefficients from any cutting test having the same cutting condition using these three calibration methods. The Kistler and Smart Tool force profile methods can be used to calibrate cutting coefficients from any single cutting test. However, one needs to determine the correct edge locating angle of the cutting tool at each instant forces are measured for calibration, as described in Chapter 5.

6.5 Summary

Cutting coefficients calibration results of the five different methods are shown and compared in this chapter. The simulated resultant cutting force using the calibrated coefficients from each method is compared to the Kistler dynamometer measured force, due to its accurate force measurements. Discussion and comparison of the five different calibration methods in terms of cost, efficiency, compliance, accuracy, repeatability and applicability is finally presented in this chapter. As we may conclude, each calibration method has its own advantages and limitations for on-line calibration of force models.
CHAPTER 7

CONCLUSIONS AND FUTURE WORK

7.1 Introduction

This chapter summarizes the thesis work and outlines the conclusions. Suggestions for future studies are also included.

7.2 Conclusions

Five different calibration methods are introduced and compared in terms of cost, efficiency, compliance, accuracy, repeatability and applicability. They are based on spindle motor power, Kistler average force and force profile, and Smart Tool average force and force profile.

A comparison of the convenience and accuracy of the various methods leads to the following conclusions:

1. Methods based on the Kistler average force and Smart Tool average force are easy to implement on-line and can lead to reasonably good simulation results, especially for half immersion cutting tests. On average, the simulated peak resultant force is within 10% of the experimental data used for calibration. However, there is a major limitation with these two calibration processes. Since average force is used to calibrate the cutting coefficients, there need to be at least two different cutting conditions to generate two different average chip thicknesses
in order to realize the calibration. Preferably, there should be at least four variations in the average chip thicknesses.

2. The Kistler and Smart Tool force profile calibration methods can provide consistent and reasonable calibration results and good simulation results. Typically, the simulated peak resultant force is within 10% of the experimental data used for calibration. However, they are hard to implement on-line because it is difficult to determine the correct edge locating angle of the cutting tool at each instant forces are measured. As mentioned before, we use the “tick signal” generated by a Hall effect sensor to determine the edge locating angle of the tool for the Kistler force profile calibration method. As for the Smart Tool, since the “tick signal” is not available, we can just estimate the edge locating angles from the force profiles, as shown in Chapter 5. Apparently, there would be cutting coefficients estimation errors associated with this process. However, these two calibration methods can be used to calibrate cutting coefficients for any cutting geometry as long as we can get a clean force profile and accurate estimation of the edge locating angles of the tool at each instant forces are measured.

3. Different sets of cutting coefficients could lead to similar estimation of the peak resultant force. The “see-saw effect”, which means higher (or lower) shearing coefficients ($K_{tc}$ or $K_{rc}$) are offset by lower (or higher) edge coefficients ($K_{te}$ or $K_{re}$), has been found consistently among almost all the calibration results. This can be verified by comparing the cutting coefficients obtained from different
methods but for the same cutting condition, or from the same force profile based method but for different feedrates. We believe the “see-saw effect” to be an artifact of the regression being applied to the cutting coefficients which are highly cross correlated [6].

4. The relative error between the simulated and measured peak resultant force is mostly less than 10% for all the calibration methods except the spindle motor power based method. This is most evident for 600 rpm cutting tests because the low spindle speed causes less tool vibration and the Kistler dynamometer’s dynamic effects can be neglected. This accuracy level would be suitable for process planning and monitoring. Since the same conditions are used for calibration and force comparison, we would expect larger errors for cuts with different spindle speeds and cut geometries.

5. The spindle motor power based method provides a simulation error of over 10% for almost all the quarter and three quarter immersion cutting tests, and even over 25% for some cases. Two possible sources could account for this: 1. the estimated cutting power from the measured spindle motor power used for calibration may not be accurate; 2. the assigned ratios of radial to tangential coefficients may not be accurate. The true reason is still under investigation and is part of the future work. However, the spindle motor power based calibration method can provide good estimation for peak resultant forces for half immersion cutting tests, with a typical error within 5% of the measured ones.
6. The force profile (both Kistler and Smart Tool) based calibration methods can provide better estimation of the peak resultant force than the average force (both Kistler and Smart Tool) based calibration methods for quarter immersion cutting tests while the latter ones can provide better estimation of the peak resultant force for half immersion cutting tests. As for three quarter immersion cutting tests, they provide comparable simulation results.

7. Each calibration method has its own advantages and limitations for on-line calibration of force models. No one method is superior.

7.3 Future Work

We have designed and conducted limited cutting tests in this research and compared the five calibration methods in terms of cost, efficiency, compliance, accuracy, repeatability and applicability. Based on what we have done so far, the future work may include:

1. More cutting tests with other cutting geometries and workpiece material such as plain steel, stainless steel and titanium, should be designed and conducted to support and verify the conclusions drawn in this research.

2. Extension to multi-tooth cutters is also essential if the force profile (both Kistler and Smart Tool) based methods are to be practical for on-line tool condition monitoring.
3. All five calibration methods presented in this research are time domain methods. While the spindle motor power based and the average force (both Kistler and Smart Tool) based calibration methods are easy to implement on-line, the force profile based calibration methods are hard to implement on-line because it is difficult to determine the correct edge locating angle of the tool during cutting. Therefore, a novel calibration method in frequency domain or a statistical force model should be investigated and developed.
REFERENCES


APPENDIX A

EXPERIMENT PROCEDURES FOR SPINDLE MOTOR POWER SENSOR

SYSTEM CALIBRATION

a. Before turning on the CNC machine, connect the Keithley digital multimeter to the power sensor.

b. Turn on the CNC machine, sync it and run the spindle at 1500 rpm for 15 minutes to warm up the spindle motor.

c. Stop the spindle and put the magnetic brake and torque sensor system on the table of the CNC machine and use two bolts and tie down clamps to fix the system on the table.

d. Use an edge finder to find the exact center of the upper shaft of the torque sensor (if there is a coupling there, please take it off first).

e. Mount the coupling to the upper shaft of the torque sensor, tighten down the clamping screw and install the collet with the rod to the spindle.

f. Use the hand wheel to make the rod fall into the hub bore of the coupling gradually. In the meantime, rotate the coupling to see whether the spindle aligns with the torque sensor well. If not, adjust the position of the table of the CNC machine to make sure they are well aligned.
g. Tighten the upper clamping screw of the coupling to make sure the coupling and the rod are strongly attached.

h. Connect the compressed air to the magnetic brake to avoid overheating (all the operators must wear ear plugs for protection).

i. Hook the magnetic brake to the BK power supply with the brown electrical cable (the brake is polarity-independent).

j. Hook the power supply, the torque sensor and Keithley digital multimeter as below:

Purple to V+, Yellow to V- on 12 v power supply. White wires are 110v into power supply. Brown to High and White to Low on 1000 v side of Keithley.

k. Turn on both Keithley and adjust their resolution to Slow 6 ½ mode (this will set the display rate on Keithley to a slow 6.5 digits readout so we can manually capture the output).

l. Run the spindle at the desired speed.

m. Turn on BK power supply, set the voltage output to 24 volts with current at zero.

n. Record the readings from the power sensor and the torque sensor simultaneously for 6 times.

o. Increase the current output from BK power supply gradually to 1 amp for low range speed and 0.6 amp for high range speed in the way mentioned in the Experiment
Setup and record the readings from the two sensors simultaneously for each current output.

p. Reset the current output from BK to zero and record the readings.

q. Change the spindle speed to the next one and repeat the procedures from n to p until all the spindle speeds are tested.
## SPINDLE MOTOR POWER SENSOR SYSTEM CALIBRATION RESULTS

Table B.1 - Spindle Motor Power Sensor System Calibration Results

<table>
<thead>
<tr>
<th>Spindle Speed (rpm)</th>
<th>Current Output from BK (amp)</th>
<th>Voltage Output From Torque Sensor (V)</th>
<th>Torque Measured (N*m)</th>
<th>Output Mechanical Power (watt)</th>
<th>Voltage Output from LCI Power Sensor (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>0.2</td>
<td>0.024</td>
<td>0.098</td>
<td>2.048</td>
<td>0.720</td>
</tr>
<tr>
<td>200</td>
<td>0.4</td>
<td>0.080</td>
<td>0.320</td>
<td>6.702</td>
<td>0.750</td>
</tr>
<tr>
<td>200</td>
<td>0.6</td>
<td>0.172</td>
<td>0.686</td>
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<td>0.808</td>
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</tr>
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<td>250</td>
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R refers to the repeated tests at the specified spindle speeds.
APPENDIX C

CUTTING COEFFICIENTS CALIBRATION RESULTS

Table C.1 - Average Force and Spindle Motor Power Based Cutting Coefficients for 600 rpm Quarter Immersion (T)

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Table C.2 - Kistler Force Profile Based Cutting Coefficients for 600 rpm Quarter Immersion (T)

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<td>$K_{rc}$ (N/mm²)</td>
<td>398.0</td>
<td>315.5390</td>
<td>281.9871</td>
<td>293.7649</td>
</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
<td>10.3</td>
<td>11.5428</td>
<td>11.9024</td>
<td>10.8373</td>
</tr>
</tbody>
</table>

Table C.3 - Smart Tool Force Profile Based Cutting Coefficients for 600 rpm Quarter Immersion (T)

<table>
<thead>
<tr>
<th></th>
<th>Feedrate 1</th>
<th>Feedrate 2</th>
<th>Feedrate 3</th>
<th>Feedrate 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{tc}$ (N/mm²)</td>
<td>1012.4</td>
<td>931.7569</td>
<td>907.4870</td>
<td>870.7193</td>
</tr>
<tr>
<td>$K_{te}$ (N/mm)</td>
<td>16.0</td>
<td>16.0682</td>
<td>14.3670</td>
<td>15.3515</td>
</tr>
<tr>
<td>$K_{rc}$ (N/mm²)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
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<td></td>
</tr>
</tbody>
</table>
Table C.4 - Average Force and Spindle Motor Power Based Cutting Coefficients for 600 rpm Quarter Immersion (R)

<table>
<thead>
<tr>
<th></th>
<th>Kistler Average Force</th>
<th>Smart Tool Average Force</th>
<th>Spindle Motor Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{tc}$ (N/mm^2)</td>
<td>727.7281</td>
<td>692.8366</td>
<td>692.8366</td>
</tr>
<tr>
<td>$K_{te}$ (N/mm)</td>
<td>22.0667</td>
<td>20.2278</td>
<td>20.2278</td>
</tr>
<tr>
<td>$K_{rc}$ (N/mm^2)</td>
<td>266.4187</td>
<td>224.7263</td>
<td>255.3796</td>
</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
<td>11.3675</td>
<td>11.1968</td>
<td>11.3741</td>
</tr>
</tbody>
</table>

Table C.5 - Kistler Force Profile Based Cutting Coefficients for 600 rpm Quarter Immersion (R)

<table>
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<tr>
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<th>Feedrate 1</th>
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<th>Feedrate 3</th>
<th>Feedrate 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{tc}$ (N/mm^2)</td>
<td>1032.7</td>
<td>873.3634</td>
<td>832.5440</td>
<td>817.8423</td>
</tr>
<tr>
<td>$K_{te}$ (N/mm)</td>
<td>11.8</td>
<td>13.9909</td>
<td>14.5534</td>
<td>13.2589</td>
</tr>
<tr>
<td>$K_{rc}$ (N/mm^2)</td>
<td>373.4</td>
<td>296.9652</td>
<td>284.7956</td>
<td>295.6732</td>
</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
<td>11.1</td>
<td>12.3155</td>
<td>11.9315</td>
<td>10.5299</td>
</tr>
</tbody>
</table>

Table C.6 - Smart Tool Force Profile Based Cutting Coefficients for 600 rpm Quarter Immersion (R)

<table>
<thead>
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<th>Feedrate 1</th>
<th>Feedrate 2</th>
<th>Feedrate 3</th>
<th>Feedrate 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{tc}$ (N/mm^2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_{te}$ (N/mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_{rc}$ (N/mm^2)</td>
<td>293.9437</td>
<td>252.4202</td>
<td>243.9677</td>
<td>241.7016</td>
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<tr>
<td>$K_{re}$ (N/mm)</td>
<td>11.3970</td>
<td>12.6690</td>
<td>12.8648</td>
<td>12.8214</td>
</tr>
</tbody>
</table>

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Table C.7 - Average Force and Spindle Motor Power Based Cutting Coefficients for 600 rpm Half Immersion (T)

<table>
<thead>
<tr>
<th></th>
<th>Kistler Average Force</th>
<th>Smart Tool Average Force</th>
<th>Spindle Motor Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{tc}$ (N/mm$^2$)</td>
<td>819.7100</td>
<td>847.2446</td>
<td>781.3918</td>
</tr>
<tr>
<td>$K_{te}$ (N/mm)</td>
<td>19.3070</td>
<td>17.6526</td>
<td>21.4889</td>
</tr>
<tr>
<td>$K_{rc}$ (N/mm$^2$)</td>
<td>291.0112</td>
<td></td>
<td>288.0210</td>
</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
<td>11.4065</td>
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<td>12.0832</td>
</tr>
</tbody>
</table>

Table C.8 - Kistler Force Profile Based Cutting Coefficients for 600 rpm Half Immersion (T)

<table>
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<tr>
<th></th>
<th>Feedrate 1</th>
<th>Feedrate 2</th>
<th>Feedrate 3</th>
<th>Feedrate 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{tc}$ (N/mm$^2$)</td>
<td>1024.9</td>
<td>997.7525</td>
<td>1000.8</td>
<td>955.1660</td>
</tr>
<tr>
<td>$K_{te}$ (N/mm)</td>
<td>12.5</td>
<td>11.4517</td>
<td>7.8</td>
<td>7.4098</td>
</tr>
<tr>
<td>$K_{rc}$ (N/mm$^2$)</td>
<td>340.0</td>
<td>328.7878</td>
<td>325.8</td>
<td>306.7606</td>
</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
<td>11.3</td>
<td>11.6809</td>
<td>10.6</td>
<td>10.7755</td>
</tr>
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</table>

Table C.9 - Smart Tool Force Profile Based Cutting Coefficients for 600 rpm Half Immersion (T)

<table>
<thead>
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<th>Feedrate 1</th>
<th>Feedrate 2</th>
<th>Feedrate 3</th>
<th>Feedrate 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{tc}$ (N/mm$^2$)</td>
<td>1109.6</td>
<td>1061.4</td>
<td>1017.0</td>
<td>958.7351</td>
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<tr>
<td>$K_{te}$ (N/mm)</td>
<td>13.2</td>
<td>13.4</td>
<td>11.9</td>
<td>12.4380</td>
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<tr>
<td>$K_{rc}$ (N/mm$^2$)</td>
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</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
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</tbody>
</table>
Table C.10 - Average Force and Spindle Motor Power Based Cutting Coefficients for 600 rpm Half Immersion (R)

<table>
<thead>
<tr>
<th></th>
<th>Kistler Average Force</th>
<th>Smart Tool Average Force</th>
<th>Spindle Motor Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{tc}$ (N/mm$^2)$</td>
<td>829.2865</td>
<td>288.0796</td>
<td>253.0700</td>
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<tr>
<td>$K_{te}$ (N/mm)</td>
<td>20.0352</td>
<td>11.4572</td>
<td>10.9745</td>
</tr>
<tr>
<td>$K_{rc}$ (N/mm$^2$)</td>
<td>1109.2</td>
<td>315.9826</td>
<td>286.2563</td>
</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
<td>10.8</td>
<td>10.4</td>
<td>10.3974</td>
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</table>

Table C.11 - Kistler Force Profile Based Cutting Coefficients for 600 rpm Half Immersion (R)

<table>
<thead>
<tr>
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<th>Feedrate 1</th>
<th>Feedrate 2</th>
<th>Feedrate 3</th>
<th>Feedrate 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{tc}$ (N/mm$^2$)</td>
<td>1109.2</td>
<td>1004.4</td>
<td>985.4192</td>
<td>927.4736</td>
</tr>
<tr>
<td>$K_{te}$ (N/mm)</td>
<td>10.8</td>
<td>11.3</td>
<td>8.7406</td>
<td>9.3591</td>
</tr>
<tr>
<td>$K_{rc}$ (N/mm$^2$)</td>
<td>384.8</td>
<td>330.2</td>
<td>328.4748</td>
<td>305.7325</td>
</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
<td>10.4</td>
<td>11.7</td>
<td>10.4895</td>
<td>10.9096</td>
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</table>

Table C.12 - Smart Tool Force Profile Based Cutting Coefficients for 600 rpm Half Immersion (R)

<table>
<thead>
<tr>
<th></th>
<th>Feedrate 1</th>
<th>Feedrate 2</th>
<th>Feedrate 3</th>
<th>Feedrate 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{tc}$ (N/mm$^2$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_{te}$ (N/mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_{rc}$ (N/mm$^2$)</td>
<td>315.9826</td>
<td>286.2563</td>
<td>290.9590</td>
<td>273.5119</td>
</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
<td>10.3974</td>
<td>11.5249</td>
<td>10.9380</td>
<td>11.3453</td>
</tr>
</tbody>
</table>
Table C.13 - Average Force and Spindle Motor Power Based Cutting Coefficients for 600 rpm Three Quarter Immersion (T)

<table>
<thead>
<tr>
<th></th>
<th>Kistler Average Force</th>
<th>Smart Tool Average Force</th>
<th>Spindle Motor Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{tc}$ (N/mm^2)</td>
<td>799.1931</td>
<td>836.5910</td>
<td>754.1463</td>
</tr>
<tr>
<td>$K_{te}$ (N/mm)</td>
<td>19.3823</td>
<td>16.1235</td>
<td>15.5865</td>
</tr>
<tr>
<td>$K_{rc}$ (N/mm^2)</td>
<td>315.1838</td>
<td>277.9783</td>
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</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
<td>10.8860</td>
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<td>8.7643</td>
</tr>
</tbody>
</table>

Table C.14 - Kistler Force Profile Based Cutting Coefficients for 600 rpm Three Quarter Immersion (T)

<table>
<thead>
<tr>
<th></th>
<th>Feedrate 1</th>
<th>Feedrate 2</th>
<th>Feedrate 3</th>
<th>Feedrate 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{tc}$ (N/mm^2)</td>
<td>946.1785</td>
<td>864.5074</td>
<td>843.9186</td>
<td>817.7775</td>
</tr>
<tr>
<td>$K_{te}$ (N/mm)</td>
<td>13.5664</td>
<td>16.5328</td>
<td>16.5556</td>
<td>16.7782</td>
</tr>
<tr>
<td>$K_{rc}$ (N/mm^2)</td>
<td>376.2954</td>
<td>320.1171</td>
<td>308.2686</td>
<td>299.7482</td>
</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
<td>10.4374</td>
<td>11.9507</td>
<td>11.6787</td>
<td>11.6541</td>
</tr>
</tbody>
</table>

Table C.15 - Smart Tool Force Profile Based Cutting Coefficients for 600 rpm Three Quarter Immersion (T)

<table>
<thead>
<tr>
<th></th>
<th>Feedrate 1</th>
<th>Feedrate 2</th>
<th>Feedrate 3</th>
<th>Feedrate 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{tc}$ (N/mm^2)</td>
<td>919.3931</td>
<td>852.2999</td>
<td>820.6392</td>
<td>801.4172</td>
</tr>
<tr>
<td>$K_{te}$ (N/mm)</td>
<td>15.7162</td>
<td>19.5255</td>
<td>21.1852</td>
<td>22.9853</td>
</tr>
<tr>
<td>$K_{rc}$ (N/mm^2)</td>
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<td></td>
</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
<td></td>
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</tbody>
</table>
Table C.16 - Average Force and Spindle Motor Power Based Cutting Coefficients for 600 rpm Three Quarter Immersion (R)

<table>
<thead>
<tr>
<th></th>
<th>Kistler Average Force</th>
<th>Smart Tool Average Force</th>
<th>Spindle Motor Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{tc}$ (N/mm^2)</td>
<td>798.0283</td>
<td>259.9289</td>
<td>760.3425</td>
</tr>
<tr>
<td>$K_{te}$ (N/mm)</td>
<td>19.5654</td>
<td>17.4579</td>
<td>15.2986</td>
</tr>
<tr>
<td>$K_{rc}$ (N/mm^2)</td>
<td>308.6772</td>
<td>259.9289</td>
<td>280.2622</td>
</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
<td>11.7959</td>
<td>10.7437</td>
<td>8.6024</td>
</tr>
</tbody>
</table>

Table C.17 - Kistler Force Profile Based Cutting Coefficients for 600 rpm Three Quarter Immersion (R)

<table>
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<tr>
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<th>Feedrate 1</th>
<th>Feedrate 2</th>
<th>Feedrate 3</th>
<th>Feedrate 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{tc}$ (N/mm^2)</td>
<td>954.1917</td>
<td>863.5857</td>
<td>829.3597</td>
<td>791.9833</td>
</tr>
<tr>
<td>$K_{te}$ (N/mm)</td>
<td>13.5895</td>
<td>16.4051</td>
<td>16.5974</td>
<td>19.7709</td>
</tr>
<tr>
<td>$K_{rc}$ (N/mm^2)</td>
<td>396.2909</td>
<td>328.8271</td>
<td>307.6162</td>
<td>289.8889</td>
</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
<td>10.2581</td>
<td>11.6738</td>
<td>12.0459</td>
<td>12.1900</td>
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</table>

Table C.18 - Smart Tool Force Profile Based Cutting Coefficients for 600 rpm Three Quarter Immersion (R)

<table>
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<th>Feedrate 2</th>
<th>Feedrate 3</th>
<th>Feedrate 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{tc}$ (N/mm^2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_{te}$ (N/mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_{rc}$ (N/mm^2)</td>
<td>347.4527</td>
<td>287.5468</td>
<td>269.3323</td>
<td>260.1320</td>
</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
<td>9.3426</td>
<td>10.8349</td>
<td>11.5118</td>
<td>11.7220</td>
</tr>
</tbody>
</table>
Table C.19 - Average Force and Spindle Motor Power Based Cutting Coefficients for 3000 rpm Quarter Immersion (T)

<table>
<thead>
<tr>
<th></th>
<th>Kistler Average Force</th>
<th>Smart Tool Average Force</th>
<th>Spindle Motor Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{tc}$ (N/mm$^2$)</td>
<td>613.5699</td>
<td>662.7393</td>
<td>614.7972</td>
</tr>
<tr>
<td>$K_{te}$ (N/mm)</td>
<td>17.8482</td>
<td>15.6311</td>
<td>12.5819</td>
</tr>
<tr>
<td>$K_{rc}$ (N/mm$^2$)</td>
<td>243.8926</td>
<td></td>
<td>243.3982</td>
</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
<td>11.2227</td>
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<td>7.9279</td>
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</tbody>
</table>

Table C.20 - Kistler Force Profile Based Cutting Coefficients for 3000 rpm Quarter Immersion (T)

<table>
<thead>
<tr>
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<th>Feedrate 1</th>
<th>Feedrate 2</th>
<th>Feedrate 3</th>
<th>Feedrate 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{tc}$ (N/mm$^2$)</td>
<td>824.3090</td>
<td>578.2028</td>
<td>559.2153</td>
<td>551.1207</td>
</tr>
<tr>
<td>$K_{te}$ (N/mm)</td>
<td>14.7075</td>
<td>25.3979</td>
<td>28.8622</td>
<td>32.5871</td>
</tr>
<tr>
<td>$K_{rc}$ (N/mm$^2$)</td>
<td>309.0714</td>
<td>177.1644</td>
<td>163.5058</td>
<td>167.9653</td>
</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
<td>11.2729</td>
<td>15.9450</td>
<td>17.7621</td>
<td>19.0909</td>
</tr>
</tbody>
</table>

Table C.21 - Smart Tool Force Profile Based Cutting Coefficients for 3000 rpm Quarter Immersion (T)

<table>
<thead>
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<th>Feedrate 1</th>
<th>Feedrate 2</th>
<th>Feedrate 3</th>
<th>Feedrate 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{tc}$ (N/mm$^2$)</td>
<td>863.24</td>
<td>657.32</td>
<td>648</td>
<td>632.5</td>
</tr>
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<td>$K_{te}$ (N/mm)</td>
<td>12.048</td>
<td>22.216</td>
<td>25.556</td>
<td>28.85</td>
</tr>
<tr>
<td>$K_{rc}$ (N/mm$^2$)</td>
<td></td>
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</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table C.22 - Average Force and Spindle Motor Power Based Cutting Coefficients for 3000 rpm Quarter Immersion (R)

<table>
<thead>
<tr>
<th></th>
<th>Kistler Average Force</th>
<th>Smart Tool Average Force</th>
<th>Spindle Motor Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{tc}$ (N/mm^2)</td>
<td>642.9063</td>
<td>244.8721</td>
<td>251.8752</td>
</tr>
<tr>
<td>$K_{te}$ (N/mm)</td>
<td>17.1140</td>
<td>11.0134</td>
<td>12.8150</td>
</tr>
<tr>
<td>$K_{rc}$ (N/mm^2)</td>
<td>182.8958</td>
<td>182.8958</td>
<td>251.8752</td>
</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
<td>12.8368</td>
<td>8.0885</td>
<td>8.0885</td>
</tr>
</tbody>
</table>

Table C.23 - Kistler Force Profile Based Cutting Coefficients for 3000 rpm Quarter Immersion (R)

<table>
<thead>
<tr>
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<th>Feedrate 1</th>
<th>Feedrate 2</th>
<th>Feedrate 3</th>
<th>Feedrate 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{tc}$ (N/mm^2)</td>
<td>821.7713</td>
<td>557.4484</td>
<td>552.9916</td>
<td>562.7009</td>
</tr>
<tr>
<td>$K_{te}$ (N/mm)</td>
<td>15.0119</td>
<td>26.1500</td>
<td>29.5650</td>
<td>31.3897</td>
</tr>
<tr>
<td>$K_{rc}$ (N/mm^2)</td>
<td>278.0837</td>
<td>141.5068</td>
<td>145.1113</td>
<td>170.0477</td>
</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
<td>11.8852</td>
<td>17.8881</td>
<td>19.5220</td>
<td>19.0292</td>
</tr>
</tbody>
</table>

Table C.24 - Smart Tool Force Profile Based Cutting Coefficients for 3000 rpm Quarter Immersion (R)

<table>
<thead>
<tr>
<th></th>
<th>Feedrate 1</th>
<th>Feedrate 2</th>
<th>Feedrate 3</th>
<th>Feedrate 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{tc}$ (N/mm^2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_{te}$ (N/mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_{rc}$ (N/mm^2)</td>
<td>174.5294</td>
<td>120.6167</td>
<td>146.1970</td>
<td>166.7926</td>
</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
<td>16.4120</td>
<td>21.7015</td>
<td>22.2501</td>
<td>21.6153</td>
</tr>
</tbody>
</table>
Table C.25 - Average Force and Spindle Motor Power Based Cutting Coefficients for 3000 rpm Half Immersion (T)

<table>
<thead>
<tr>
<th></th>
<th>Kistler Average Force</th>
<th>Smart Tool Average Force</th>
<th>Spindle Motor Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{fc}$ (N/mm$^2$)</td>
<td>671.4461</td>
<td>689.3335</td>
<td>697.1742</td>
</tr>
<tr>
<td>$K_{fe}$ (N/mm)</td>
<td>21.8295</td>
<td>18.5568</td>
<td>18.0530</td>
</tr>
<tr>
<td>$K_{rc}$ (N/mm$^2$)</td>
<td>232.9034</td>
<td></td>
<td>276.0113</td>
</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
<td>14.0712</td>
<td></td>
<td>11.3752</td>
</tr>
</tbody>
</table>

Table C.26 - Kistler Force Profile Based Cutting Coefficients for 3000 rpm Half Immersion (T)

<table>
<thead>
<tr>
<th></th>
<th>Feedrate 1</th>
<th>Feedrate 2</th>
<th>Feedrate 3</th>
<th>Feedrate 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{fc}$ (N/mm$^2$)</td>
<td>902.2263</td>
<td>749.2887</td>
<td>740.5189</td>
<td>720.9159</td>
</tr>
<tr>
<td>$K_{fe}$ (N/mm)</td>
<td>14.3096</td>
<td>18.9551</td>
<td>18.6971</td>
<td>18.4253</td>
</tr>
<tr>
<td>$K_{rc}$ (N/mm$^2$)</td>
<td>385.6796</td>
<td>267.1295</td>
<td>251.1433</td>
<td>237.2776</td>
</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
<td>12.2137</td>
<td>15.3964</td>
<td>16.0096</td>
<td>16.3868</td>
</tr>
</tbody>
</table>

Table C.27 - Smart Tool Force Profile Based Cutting Coefficients for 3000 rpm Half Immersion (T)

<table>
<thead>
<tr>
<th></th>
<th>Feedrate 1</th>
<th>Feedrate 2</th>
<th>Feedrate 3</th>
<th>Feedrate 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{fc}$ (N/mm$^2$)</td>
<td>812.8</td>
<td>768.07</td>
<td>801.72</td>
<td>767.42</td>
</tr>
<tr>
<td>$K_{fe}$ (N/mm)</td>
<td>19.45</td>
<td>22.107</td>
<td>19.401</td>
<td>21.43</td>
</tr>
<tr>
<td>$K_{rc}$ (N/mm$^2$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table C.28 - Average Force and Spindle Motor Power Based Cutting Coefficients for 3000 rpm Half Immersion (R)

<table>
<thead>
<tr>
<th></th>
<th>Kistler Average Force</th>
<th>Smart Tool Average Force</th>
<th>Spindle Motor Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{tc}$ (N/mm^2)</td>
<td>676.4707</td>
<td>738.8071</td>
<td></td>
</tr>
<tr>
<td>$K_{te}$ (N/mm)</td>
<td>21.5677</td>
<td>18.4991</td>
<td></td>
</tr>
<tr>
<td>$K_{re}$ (N/mm^2)</td>
<td>234.2961</td>
<td>192.5107</td>
<td>292.4937</td>
</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
<td>13.8505</td>
<td>14.1201</td>
<td>11.6563</td>
</tr>
</tbody>
</table>

Table C.29 - Kistler Force Profile Based Cutting Coefficients for 3000 rpm Half Immersion (R)

<table>
<thead>
<tr>
<th></th>
<th>Feedrate 1</th>
<th>Feedrate 2</th>
<th>Feedrate 3</th>
<th>Feedrate 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{tc}$ (N/mm^2)</td>
<td>920.8222</td>
<td>731.6559</td>
<td>768.0431</td>
<td>723.2580</td>
</tr>
<tr>
<td>$K_{te}$ (N/mm)</td>
<td>13.9447</td>
<td>19.0729</td>
<td>16.4577</td>
<td>18.5387</td>
</tr>
<tr>
<td>$K_{re}$ (N/mm^2)</td>
<td>400.3115</td>
<td>267.9117</td>
<td>275.2306</td>
<td>238.0865</td>
</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
<td>11.6614</td>
<td>15.5432</td>
<td>14.4955</td>
<td>15.6561</td>
</tr>
</tbody>
</table>

Table C.30 - Smart Tool Force Profile Based Cutting Coefficients for 3000 rpm Half Immersion (R)

<table>
<thead>
<tr>
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<th>Feedrate 1</th>
<th>Feedrate 2</th>
<th>Feedrate 3</th>
<th>Feedrate 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{tc}$ (N/mm^2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_{te}$ (N/mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_{re}$ (N/mm^2)</td>
<td>205.9839</td>
<td>154.3716</td>
<td>184.5939</td>
<td>159.8609</td>
</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
<td>14.7884</td>
<td>18.8047</td>
<td>18.5888</td>
<td>21.0035</td>
</tr>
</tbody>
</table>
Table C.31 - Average Force and Spindle Motor Power Based Cutting Coefficients for 3000 rpm Three Quarter Immersion (T)

<table>
<thead>
<tr>
<th></th>
<th>Kistler Average Force</th>
<th>Smart Tool Average Force</th>
<th>Spindle Motor Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{tc}$ (N/mm²)</td>
<td>656.8417</td>
<td>761.5866</td>
<td>738.6378</td>
</tr>
<tr>
<td>$K_{te}$ (N/mm)</td>
<td>19.6580</td>
<td>17.8042</td>
<td>13.8394</td>
</tr>
<tr>
<td>$K_{rc}$ (N/mm²)</td>
<td>301.1310</td>
<td></td>
<td>292.4267</td>
</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
<td>11.2332</td>
<td></td>
<td>8.7202</td>
</tr>
</tbody>
</table>

Table C.32 - Kistler Force Profile Based Cutting Coefficients for 3000 rpm Three Quarter Immersion (T)

<table>
<thead>
<tr>
<th></th>
<th>Feedrate 1</th>
<th>Feedrate 2</th>
<th>Feedrate 3</th>
<th>Feedrate 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{tc}$ (N/mm²)</td>
<td>773.7842</td>
<td>673.9103</td>
<td>676.4758</td>
<td>672.9911</td>
</tr>
<tr>
<td>$K_{te}$ (N/mm)</td>
<td>15.1519</td>
<td>20.0383</td>
<td>21.4392</td>
<td>20.5569</td>
</tr>
<tr>
<td>$K_{rc}$ (N/mm²)</td>
<td>377.9153</td>
<td>275.9240</td>
<td>250.4006</td>
<td>240.0820</td>
</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
<td>11.1882</td>
<td>14.2210</td>
<td>15.7230</td>
<td>16.3100</td>
</tr>
</tbody>
</table>

Table C.33 - Smart Tool Force Profile Based Cutting Coefficients for 3000 rpm Three Quarter Immersion (T)

<table>
<thead>
<tr>
<th></th>
<th>Feedrate 1</th>
<th>Feedrate 2</th>
<th>Feedrate 3</th>
<th>Feedrate 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{tc}$ (N/mm²)</td>
<td>883.7097</td>
<td>768.9125</td>
<td>776.8609</td>
<td>781.4713</td>
</tr>
<tr>
<td>$K_{te}$ (N/mm)</td>
<td>13.9690</td>
<td>18.0664</td>
<td>17.2415</td>
<td>13.4155</td>
</tr>
<tr>
<td>$K_{rc}$ (N/mm²)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table C.34 - Average Force and Spindle Motor Power Based Cutting Coefficients for 3000 rpm Three Quarter Immersion (R)

<table>
<thead>
<tr>
<th></th>
<th>Kistler Average Force</th>
<th>Smart Tool Average Force</th>
<th>Spindle Motor Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{tc}$ (N/mm^2)</td>
<td>672.8909</td>
<td>299.3752</td>
<td></td>
</tr>
<tr>
<td>$K_{te}$ (N/mm)</td>
<td>18.8466</td>
<td>12.2490</td>
<td></td>
</tr>
<tr>
<td>$K_{rc}$ (N/mm^2)</td>
<td>233.5516</td>
<td>233.5516</td>
<td></td>
</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
<td>13.0211</td>
<td>9.7339</td>
<td></td>
</tr>
</tbody>
</table>

Table C.35 - Kistler Force Profile Based Cutting Coefficients for 3000 rpm Three Quarter Immersion (R)

<table>
<thead>
<tr>
<th></th>
<th>Feedrate 1</th>
<th>Feedrate 2</th>
<th>Feedrate 3</th>
<th>Feedrate 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{tc}$ (N/mm^2)</td>
<td>713.8636</td>
<td>677.4449</td>
<td>697.1114</td>
<td>674.3120</td>
</tr>
<tr>
<td>$K_{te}$ (N/mm)</td>
<td>17.2368</td>
<td>19.1035</td>
<td>19.8320</td>
<td>22.3713</td>
</tr>
<tr>
<td>$K_{rc}$ (N/mm^2)</td>
<td>334.1894</td>
<td>276.5013</td>
<td>268.7876</td>
<td>238.0956</td>
</tr>
<tr>
<td>$K_{re}$ (N/mm)</td>
<td>12.4858</td>
<td>14.1964</td>
<td>14.6687</td>
<td>16.6682</td>
</tr>
</tbody>
</table>

Table C.36 - Smart Tool Force Profile Based Cutting Coefficients for 3000 rpm Three Quarter Immersion (R)

<table>
<thead>
<tr>
<th></th>
<th>Feedrate 1</th>
<th>Feedrate 2</th>
<th>Feedrate 3</th>
<th>Feedrate 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{tc}$ (N/mm^2)</td>
<td>133.7280</td>
<td>149.3496</td>
<td>213.0565</td>
<td>201.1375</td>
</tr>
<tr>
<td>$K_{te}$ (N/mm)</td>
<td>15.9564</td>
<td>18.1526</td>
<td>16.0614</td>
<td>17.0142</td>
</tr>
</tbody>
</table>
**APPENDIX D**

**SIMULATION RESULTS**

Table D.1 - REp for 600 rpm Quarter Immersion (T)

<table>
<thead>
<tr>
<th>Feedrate</th>
<th>Kistler Average Force</th>
<th>Smart Tool Average Force</th>
<th>Spindle Motor Power</th>
<th>Kistler Force Profile</th>
<th>Smart Tool Force Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedrate 1</td>
<td>-10.88</td>
<td>-13.21</td>
<td>-17.8</td>
<td>0.19</td>
<td>-0.15</td>
</tr>
<tr>
<td>Feedrate 2</td>
<td>-9.84</td>
<td>-9.82</td>
<td>-15.92</td>
<td>-1.51</td>
<td>0.76</td>
</tr>
<tr>
<td>Feedrate 3</td>
<td>-7.01</td>
<td>-5.83</td>
<td>-12.85</td>
<td>-2.03</td>
<td>2.81</td>
</tr>
<tr>
<td>Feedrate 4</td>
<td>-2.9</td>
<td>-0.97</td>
<td>-8.74</td>
<td>-3.61</td>
<td>5.75</td>
</tr>
</tbody>
</table>

Table D.2 - REp for 600 rpm Quarter Immersion (R)

<table>
<thead>
<tr>
<th>Feedrate</th>
<th>Kistler Average Force</th>
<th>Smart Tool Average Force</th>
<th>Spindle Motor Power</th>
<th>Kistler Force Profile</th>
<th>Smart Tool Force Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedrate 1</td>
<td>-7.69</td>
<td>-10.75</td>
<td>-12.83</td>
<td>0.04</td>
<td>2.68</td>
</tr>
<tr>
<td>Feedrate 2</td>
<td>-11.92</td>
<td>-11.53</td>
<td>-16.57</td>
<td>-6.3</td>
<td>-1.15</td>
</tr>
<tr>
<td>Feedrate 3</td>
<td>-10.86</td>
<td>-8.87</td>
<td>-15.44</td>
<td>-5.86</td>
<td>-0.51</td>
</tr>
<tr>
<td>Feedrate 4</td>
<td>-6.72</td>
<td>-3.67</td>
<td>-11.43</td>
<td>-1.91</td>
<td>2.87</td>
</tr>
</tbody>
</table>
Table D.3 - REp for 600 rpm Half Immersion (T)

<table>
<thead>
<tr>
<th></th>
<th>Kistler Average Force</th>
<th>Smart Tool Average Force</th>
<th>Spindle Motor Power</th>
<th>Kistler Force Profile</th>
<th>Smart Tool Force Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedrate 1</td>
<td>1.01</td>
<td>-1.25</td>
<td>2.48</td>
<td>4.58</td>
<td>9.92</td>
</tr>
<tr>
<td>Feedrate 3</td>
<td>-2.75</td>
<td>-2.9</td>
<td>-4.38</td>
<td>5.48</td>
<td>8.84</td>
</tr>
<tr>
<td>Feedrate 4</td>
<td>0.6</td>
<td>0.84</td>
<td>-1.64</td>
<td>6.69</td>
<td>9.01</td>
</tr>
</tbody>
</table>

Table D.4 - REp for 600 rpm Half Immersion (R)

<table>
<thead>
<tr>
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<th>Kistler Average Force</th>
<th>Smart Tool Average Force</th>
<th>Spindle Motor Power</th>
<th>Kistler Force Profile</th>
<th>Smart Tool Force Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedrate 1</td>
<td>1.22</td>
<td>-2.74</td>
<td>0.59</td>
<td>6.29</td>
<td>8.26</td>
</tr>
<tr>
<td>Feedrate 2</td>
<td>-1.86</td>
<td>-4.04</td>
<td>-3.49</td>
<td>4.7</td>
<td>9.87</td>
</tr>
<tr>
<td>Feedrate 3</td>
<td>-1.74</td>
<td>-3.14</td>
<td>-3.83</td>
<td>4.62</td>
<td>8.56</td>
</tr>
<tr>
<td>Feedrate 4</td>
<td>0.96</td>
<td>-0.02</td>
<td>-1.47</td>
<td>4.35</td>
<td>8.09</td>
</tr>
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</table>
Table D.5 - REp for 600 rpm Three Quarter Immersion (T)

<table>
<thead>
<tr>
<th>Feedrate</th>
<th>Kistler Average Force</th>
<th>Smart Tool Average Force</th>
<th>Spindle Motor Power</th>
<th>Kistler Force Profile</th>
<th>Smart Tool Force Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedrate 1</td>
<td>0.94</td>
<td>-4.1</td>
<td>-11.22</td>
<td>1.33</td>
<td>1.66</td>
</tr>
<tr>
<td>Feedrate 2</td>
<td>-3.53</td>
<td>-5.98</td>
<td>-13.17</td>
<td>-0.97</td>
<td>-0.23</td>
</tr>
<tr>
<td>Feedrate 3</td>
<td>-2.67</td>
<td>-4</td>
<td>-11.47</td>
<td>-1.13</td>
<td>-0.76</td>
</tr>
<tr>
<td>Feedrate 4</td>
<td>-0.14</td>
<td>-0.81</td>
<td>-8.62</td>
<td>-0.5</td>
<td>0.65</td>
</tr>
</tbody>
</table>

Table D.6 - REp for 600 rpm Three Quarter Immersion (R)

<table>
<thead>
<tr>
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<th>Smart Tool Average Force</th>
<th>Spindle Motor Power</th>
<th>Kistler Force Profile</th>
<th>Smart Tool Force Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedrate 1</td>
<td>-0.09</td>
<td>-5.83</td>
<td>-12.99</td>
<td>0.48</td>
<td>-0.17</td>
</tr>
<tr>
<td>Feedrate 2</td>
<td>-3.18</td>
<td>-5.95</td>
<td>-12.98</td>
<td>-0.98</td>
<td>-0.19</td>
</tr>
<tr>
<td>Feedrate 3</td>
<td>-2.15</td>
<td>-3.6</td>
<td>-10.78</td>
<td>-1.81</td>
<td>-0.35</td>
</tr>
<tr>
<td>Feedrate 4</td>
<td>-0.82</td>
<td>-1.49</td>
<td>-8.83</td>
<td>-1.83</td>
<td>-0.04</td>
</tr>
</tbody>
</table>
### Table D.7 - REp for 3000 rpm Quarter Immersion (T)

<table>
<thead>
<tr>
<th>Feedrate</th>
<th>Kistler Average Force</th>
<th>Smart Tool Average Force</th>
<th>Spindle Motor Power</th>
<th>Kistler Force Profile</th>
<th>Smart Tool Force Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-13.36</td>
<td>-14.22</td>
<td>-23.89</td>
<td>-1.39</td>
<td>-3.48</td>
</tr>
<tr>
<td>2</td>
<td>-10.62</td>
<td>-10.05</td>
<td>-17.4</td>
<td>-6.7</td>
<td>-2.36</td>
</tr>
<tr>
<td>3</td>
<td>-11.82</td>
<td>-10.5</td>
<td>-16.66</td>
<td>-10.37</td>
<td>-3.26</td>
</tr>
<tr>
<td>4</td>
<td>-7.97</td>
<td>-6.11</td>
<td>-11.92</td>
<td>-7.22</td>
<td>0.05</td>
</tr>
</tbody>
</table>

### Table D.8 - REp for 3000 rpm Quarter Immersion (R)

<table>
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<tr>
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<th>Kistler Average Force</th>
<th>Smart Tool Average Force</th>
<th>Spindle Motor Power</th>
<th>Kistler Force Profile</th>
<th>Smart Tool Force Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-18.49</td>
<td>-20.02</td>
<td>-26.9</td>
<td>-8.32</td>
<td>-10</td>
</tr>
<tr>
<td>3</td>
<td>-13.44</td>
<td>-14.42</td>
<td>-17.7</td>
<td>-14.59</td>
<td>-7.5</td>
</tr>
<tr>
<td>4</td>
<td>-7.59</td>
<td>-8.45</td>
<td>-11.26</td>
<td>-8.93</td>
<td>-2.45</td>
</tr>
</tbody>
</table>

### Table D.9 - REp for 3000 rpm Half Immersion (T)

<table>
<thead>
<tr>
<th>Feedrate</th>
<th>Kistler Average Force</th>
<th>Smart Tool Average Force</th>
<th>Spindle Motor Power</th>
<th>Kistler Force Profile</th>
<th>Smart Tool Force Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.6</td>
<td>-6.1</td>
<td>-5.95</td>
<td>5.72</td>
<td>4.57</td>
</tr>
<tr>
<td>2</td>
<td>-4.3</td>
<td>-7.71</td>
<td>-5.79</td>
<td>1.18</td>
<td>3.67</td>
</tr>
<tr>
<td>3</td>
<td>-1.96</td>
<td>-4.44</td>
<td>-1.68</td>
<td>3.66</td>
<td>8.56</td>
</tr>
<tr>
<td>4</td>
<td>1.26</td>
<td>-0.66</td>
<td>2.65</td>
<td>5.12</td>
<td>10.34</td>
</tr>
</tbody>
</table>
Table D.10 - REp for 3000 rpm Half Immersion (R)

<table>
<thead>
<tr>
<th>Feedrate</th>
<th>Kistler Average Force</th>
<th>Smart Tool Average Force</th>
<th>Spindle Motor Power</th>
<th>Kistler Force Profile</th>
<th>Smart Tool Force Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-2.5</td>
<td>-7.67</td>
<td>-3.35</td>
<td>4.57</td>
<td>2.82</td>
</tr>
<tr>
<td>2</td>
<td>-3.91</td>
<td>-7.43</td>
<td>-0.72</td>
<td>0.23</td>
<td>3.98</td>
</tr>
<tr>
<td>3</td>
<td>-2.58</td>
<td>-5.3</td>
<td>2.6</td>
<td>4.05</td>
<td>7.58</td>
</tr>
<tr>
<td>4</td>
<td>2.01</td>
<td>-0.29</td>
<td>8.64</td>
<td>5.68</td>
<td>10.75</td>
</tr>
</tbody>
</table>

Table D.11 - REp for 3000 rpm Three Quarter Immersion (T)

<table>
<thead>
<tr>
<th>Feedrate</th>
<th>Kistler Average Force</th>
<th>Smart Tool Average Force</th>
<th>Spindle Motor Power</th>
<th>Kistler Force Profile</th>
<th>Smart Tool Force Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-5.06</td>
<td>-2.3</td>
<td>-12.67</td>
<td>-3.16</td>
<td>-1.92</td>
</tr>
<tr>
<td>2</td>
<td>-5.75</td>
<td>-0.84</td>
<td>-7.46</td>
<td>-3.25</td>
<td>-0.31</td>
</tr>
<tr>
<td>3</td>
<td>-9.74</td>
<td>-3.94</td>
<td>-8.66</td>
<td>-6.9</td>
<td>-2.76</td>
</tr>
<tr>
<td>4</td>
<td>-11.66</td>
<td>-5.33</td>
<td>-9.02</td>
<td>-10.66</td>
<td>-6.51</td>
</tr>
</tbody>
</table>

Table D.12 - REp for 3000 rpm Three Quarter Immersion (R)

<table>
<thead>
<tr>
<th>Feedrate</th>
<th>Kistler Average Force</th>
<th>Smart Tool Average Force</th>
<th>Spindle Motor Power</th>
<th>Kistler Force Profile</th>
<th>Smart Tool Force Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-5.06</td>
<td>-2.76</td>
<td>-9.08</td>
<td>-3.94</td>
<td>-2.39</td>
</tr>
<tr>
<td>2</td>
<td>-3.97</td>
<td>0.1</td>
<td>-3.76</td>
<td>-3.11</td>
<td>0.63</td>
</tr>
<tr>
<td>3</td>
<td>-12.82</td>
<td>-8.29</td>
<td>-10.76</td>
<td>-10.34</td>
<td>-7.17</td>
</tr>
<tr>
<td>4</td>
<td>-13.61</td>
<td>-8.62</td>
<td>-10.49</td>
<td>-12.5</td>
<td>-9.77</td>
</tr>
</tbody>
</table>
APPENDIX E

MATLAB PROGRAMS

Force Model Calibration Using Kistler Average Force and Spindle Motor Power

%%% Calibrate the cutting coefficients using average force from the
%%% Kistler force dynamometer and the average power from the LCI sensor
%%% for standard cutting test
%%% Program can be used in down milling and up milling

%%% Input: cutting geometry and measured data file for Kistler and LCI
%%% power sensor
%%% Output: cutting coefficients calibrated from the Kistler average
%%% force and the spindle motor power methods

%%% By Yong Zhao
%%% Revised on February 09 2012
%%% Design and Manufacturing Lab, University of New Hampshire

clc;
close all;
clear all;

%%
rpm=600;
fs=7200; % Sampling frequency
numpercycle=60*fs/rpm;
cycles=20; % number of cycles of force to be used
degree=0.5; % data sampling at every 3 degree of tool rotation
N=1; % number of tooth
AD=0.125; % axial depth unit:inch
D=0.75; % diameter of the tool unit: inch

%%% motor coefficient for 600 rpm
motor_efficiency=0.982;
Ptare=174; % measured data from a recent 600 rpm cutting test unit: watt

%%% motor coefficient for 3000 rpm
motor_efficiency=0.918;
Ptare=365;

%%% motor coefficient for 3600 rpm
motor_efficiency=0.883;

- 104 -
% F_tare=400;

% motor coefficient for 4000 rpm
% motor efficiency=0.865;
% F_tare=450;

j=6; % i=1,2 and 3 means down milling 1/4 immersion, 1/2 immersion and 3/4 immersion; i=4,5 and 6 means up milling 1/4 immersion, 1/2 immersion and 3/4 immersion.

if j==1
    disp('Quarter Immersion Down Milling');
    enter=2/3*pi;
    exit=pi;
    Theta=1/3*pi;
    RD=1/4*D; % radial depth quarter immersion unit: inch
    Feed=[5.445 10.891 16.336 21.782]'; % feedrate unit:inch/min
elseif j==2
    disp('Half Immersion Down Milling');
    enter=1/2*pi;
    exit=pi;
    Theta=1/2*pi;
    RD=1/2*D; % radial depth half immersion unit: inch
    Feed=[4.084 8.168 12.252 16.336]'; % feedrate unit:inch/min
elseif j==3
    disp('Three Quarter Immersion Down Milling');
    enter=1/3*pi;
    exit=pi;
    Theta=2/3*pi;
    RD=3/4*D; % radial depth three quarter immersion unit: inch
    Feed=[3.63 7.261 10.891 14.521]'; % feedrate unit:inch/min
elseif j==4
    disp('Quarter Immersion Up Milling');
    enter=0;
    exit=1/3*pi;
    Theta=1/3*pi;
    RD=1/4*D; % radial depth quarter immersion unit: inch
    Feed=[1.257 2.513 3.770 5.027]'; % feedrate unit:inch/min
    %Feed=[6.283 12.566 18.850 25.133]'; % feedrate for 3000 rpm
    %Feed=[7.540 15.080 22.619 30.159]'; % feedrate for 3600 rpm
    %Feed=[8.378 16.755 25.133 33.510]'; % feedrate for 4000 rpm
elseif j==5
    disp('Half Immersion Up Milling');
    enter=0;
    exit=1/2*pi;
    Theta=1/2*pi;
    RD=1/2*D; % radial depth half immersion unit: inch
    Feed=[0.942 1.885 2.827 3.770]'; % feedrate unit:inch/min
    %Feed=[4.712 9.425 14.137 18.850]'; % feedrate for 3000 rpm
    %Feed=[5.655 11.310 16.965 22.619]'; % feedrate for 3600 rpm
```matlab
% Feed=[6.283 12.566 18.850 25.133]'; % feedrate for 4000 rpm
elseif j==6
disp('Three Quarter Immersion Up Milling');
enter=0;
exit=2/3*pi;
Theta=2/3*pi;
RD=3/4*D; % radial depth three quarter immersion unit: inch
Feed=[0.838 1.676 2.513 3.351]'; % feedrate for 600 rpm
\% Feed=[4.189 8.378 12.566 16.755]'; % feedrate for 3000 rpm
\% Feed=[5.027 10.053 15.080 20.106]'; % feedrate for 3600 rpm
\% Feed=[5.585 11.170 16.755 22.340]'; % feedrate for 4000 rpm
end

Fx=zeros(4,1);
Fy=zeros(4,1);

\% Read the data file
[fileName,PathName,FilterIndex] = uigetfile('*.csv', 'Please choose an excel file to calibrate the cutting coefficients');
if( fileName == 0 )
    return;
end;
fname = sprintf('%s%s', PathName, fileName)
[a b c]=xlsread(fname);

\% Nfiles=2;
\% filename='Aluminum3k36k4kQuarterUpRadial';
\% a=[];
\% for n = 1:Nfiles
\%     \% Name of sub-file to read
\%     namespace = strcat(filename,int2str(n-1),'.csv');
\%     \% Read xls data
\%     [newdata, headertext] = xlsread(namespace);
\%     \% Concatenate data
\%     a = vertcat(a,newdata);
\% end

\% Plot raw Fx and Fy from Kistler
a(:,2)=-a(:,2);
a(:,3)=-a(:,3);

\% figure
subplot(2,1,1)
plot(a(:,1),a(:,2));
title('Raw Force Data from Kistler in X Direction');
xlabel('Time (s)');
```
ylabel('Fx (volt)');

subplot(2,1,2)
plot(a(:,1),a(:,3));
title('Raw Force Data from Kistler in Y Direction');
xlabel('Time (s)');
ylabel('Fy (volt)');

figure
subplot(2,1,1)
plot(a(:,1),a(:,2));
title('Raw Force Data from Kistler in X Direction');
xlabel('Time (s)');
ylabel('Fx (volt)');

subplot(2,1,2)
plot(a(:,1),a(:,5));
title('Raw Power Data from LCI');
xlabel('Time (s)');
ylabel('Power (volt)');

% plot raw Fx
numl=cursor_info_0.DataIndex;
num2=cursor_info_00.DataIndex;
disp('Kistler zero offset at X and Y direction in the end');
Fx_zero_offset=mean(a(numl:num2,2))
Fy_zero_offset=mean(a(numl:num2,3))
a(:,2)=a(:,2)-Fx_zero_offset;
a(:,3)=a(:,3)-Fy_zero_offset;

figure;
plot(a(:,1),a(:,2));
title('Raw Force Data from Kistler in X Direction');
xlabel('Time (s)');
ylabel('Fx (volt)');

cycles=20;
figure
startnum=cursor_info_1.DataIndex;
endnum=startnum+numpercycle*cycles-1;
time=a(startnum:endnum,1);
Fx_raw=500*a(startnum:endnum,2);
Fy_raw=500*a(startnum:endnum,3);
Pe=a(startnum:endnum,5)/10*2.006*746; % unit:watt
plot(time,Fx_raw);
Fx(1,1) = mean(Fx_raw);
Fy(1,1) = mean(Fy_raw);
Pcut(1,1) = (mean(Pe) - Ptare) * motor_efficiency;

%%
% plot raw force data in X direction for the second feedrate calculate
% the mean of the raw force and cutting power
figure
startnum = cursor_info_2.DataIndex;
endnum = startnum + numpercycle*cycles-1;
time = a(startnum:endnum,1);
Fx_raw = 500*a(startnum:endnum,2);
Fy_raw = 500*a(startnum:endnum,3);
Pe = a(startnum:endnum,5)/10*2.006*746;
plot(time,Fx_raw);

Fx(2,1) = mean(Fx_raw);
Fy(2,1) = mean(Fy_raw);
Pcut(2,1) = (mean(Pe) - Ptare) * motor_efficiency;

%%
% plot raw force data in X direction for the third feedrate and calculate
% the mean of the raw force and cutting power
figure
startnum = cursor_info_3.DataIndex;
endnum = startnum + numpercycle*cycles-1;
time = a(startnum:endnum,1);
Fx_raw = 500*a(startnum:endnum,2);
Fy_raw = 500*a(startnum:endnum,3);
Pe = a(startnum:endnum,5)/10*2.006*746;
plot(time,Fx_raw);

Fx(3,1) = mean(Fx_raw);
Fy(3,1) = mean(Fy_raw);
Pcut(3,1) = (mean(Pe) - Ptare) * motor_efficiency;

%%
% plot raw force data in X direction for the fourth feedrate and calculate
% the mean of the raw force and cutting power
figure
startnum = cursor_info_4.DataIndex;
endnum = startnum + numpercycle*cycles-1;
time = a(startnum:endnum,1);
Fx_raw = 500*a(startnum:endnum,2);
Fy_raw = 500*a(startnum:endnum,3);
Pe = a(startnum:endnum,5)/10*2.006*746;
plot(time,Fx_raw);

Fx(4,1) = mean(Fx_raw);
Fy(4,1) = mean(Fy_raw);
Pcut(4,1) = (mean(Fe) - Ptare) * motor_efficiency;

\text{Using the averaged force and power to calibrate the cutting coefficients}

Q_dot = AD * RD * Feed / 60 * 25.4^3; \text{% material removal rate unit: mm}^3/\text{s}
Ac_dot = D / 2 * \Theta * rpm * AD / 60 * 25.4^2; \text{% contact area rate unit: mm}^2/\text{s}
Ac dot = [Ac dot Ac dot Ac dot Ac dot]';
G = [Q dot Ac dot];
Kt = inv(G * G') * (Pcut) * 1000;

if j < 4
  for i = 1:4
    fp(i) = Feed(i) / (N * rpm);
    A1x(i) = 25.4^2 * N * AD * fp(i) / (2 * pi) * (cos(2 * exit) - cos(2 * enter));
    A2x(i) = -25.4 * N * AD / (2 * pi) * (sin(exit) - sin(enter));
    A3x(i) = -25.4^2 * N * AD * fp(i) / (2 * pi) * (2 * exit - 2 * enter -
             sin(2 * exit) + sin(2 * enter));
    A4x(i) = 25.4 * N * AD / (2 * pi) * (cos(exit) - cos(enter));

    A1y(i) = 25.4^2 * N * AD * fp(i) / (2 * pi) * (2 * exit - 2 * enter -
             sin(2 * exit) + sin(2 * enter));
    A2y(i) = -25.4 * N * AD / (2 * pi) * (cos(exit) - cos(enter));
    A3y(i) = 25.4^2 * N * AD * fp(i) / (2 * pi) * (cos(2 * exit) - cos(2 * enter));
    A4y(i) = -25.4 * N * AD / (2 * pi) * (sin(exit) - sin(enter));
  end
else
  for i = 1:4
    fp(i) = Feed(i) / (N * rpm);
    A1x(i) = 25.4^2 * N * AD * fp(i) / (2 * pi) * (cos(2 * exit) - cos(2 * enter));
    A2x(i) = -25.4 * N * AD / (2 * pi) * (sin(exit) - sin(enter));
    A3x(i) = -25.4^2 * N * AD * fp(i) / (2 * pi) * (2 * exit - 2 * enter -
             sin(2 * exit) + sin(2 * enter));
    A4x(i) = 25.4 * N * AD / (2 * pi) * (cos(exit) - cos(enter));

    A1y(i) = 25.4^2 * N * AD * fp(i) / (2 * pi) * (2 * exit - 2 * enter -
             sin(2 * exit) + sin(2 * enter));
    A2y(i) = -25.4 * N * AD / (2 * pi) * (cos(exit) - cos(enter));
    A3y(i) = 25.4^2 * N * AD * fp(i) / (2 * pi) * (cos(2 * exit) - cos(2 * enter));
    A4y(i) = -25.4 * N * AD / (2 * pi) * (sin(exit) - sin(enter));
  end
end

M = [A1x(1) A2x(1) A3x(1) A4x(1); A1y(1) A2y(1) A3y(1) A4y(1);
      A1x(2) A2x(2) A3x(2) A4x(2); A1y(2) A2y(2) A3y(2) A4y(2);
      A1x(3) A2x(3) A3x(3) A4x(3); A1y(3) A2y(3) A3y(3) A4y(3);
      A1x(4) A2x(4) A3x(4) A4x(4); A1y(4) A2y(4) A3y(4) A4y(4)];

F = [Fx(1); Fy(1); Fx(2); Fy(2); Fx(3); Fy(3); Fx(4); Fy(4)];
\[ K = \text{inv}(M' \cdot M) \cdot M' \cdot F; \]

```matlab
%%
% display the cutting coefficients

disp('Using the averaged force Fx and Fy');
K
Kt
```

**Force Model Calibration Using Smart Tool Average Force**

```matlab
%%
% Calibrate the cutting coefficients using average force from Smart Tool
% for standard cutting test
% Program can be used in down milling and up milling

%% Input: cutting geometry and measured data file for Smart Tool
% Output: cutting coefficients calibrated from the Smart Tool average force methods

% By Yong Zhao
% Revised on February 13 2012
% Design and Manufacturing Lab, University of New Hampshire

c1c;
close all;
clear all;

%%
rpm=600;
fs=10240;
N=1; % number of tooth
AD=0.125; % axial depth unit: inch
D=0.75; % diameter of the tool unit: inch

k=1; % k=1 tangential coefficients calibration; k=2 radial coefficients calibration
j=6; % j=1, 2 and 3 means down milling 1/4 immersion, 1/2 immersion and 3/4 immersion; j=4, 5 and 6 means up milling 1/4 immersion, 1/2 immersion and 3/4 immersion.
if j==1
    disp('Quarter Immersion Down Milling');
    enter=2/3*pi;
    exit=pi;
    Theta=1/3*pi;
    RD=1/4*D; % radial depth quarter immersion unit: inch
    Feed=[5.445 10.891 16.336 21.782]'; % feedrate unit: inch/min
```
elseif j==2
    disp('Half Immersion Down Milling');
    enter=1/2*pi;
    exit=pi;
    Theta=1/2*pi;
    RD=1/2*D; % radial depth half immersion unit: inch
    Feed=[4.084 8.168 12.252 16.336]'; % feedrate unit: inch/min
elseif j==3
    disp('Three Quarter Immersion Down Milling');
    enter=1/3*pi;
    exit=pi;
    Theta=2/3*pi;
    RD=3/4*D; % radial depth three quarter immersion unit: inch
    Feed=[3.63 7.261 10.891 14.521]'; % feedrate unit: inch/min
elseif j==4
    disp('Quarter Immersion Up Milling');
    enter=0;
    exit=1/3*pi;
    Theta=1/3*pi;
    RD=1/4*D; % radial depth quarter immersion unit: inch
    Feed=[1.257 2.513 3.770 5.027]'; % feedrate for 600 rpm unit: inch/min
    %Feed=[6.283 12.566 18.850 25.133]'; % feedrate for 3000 rpm
    %Feed=[7.540 15.080 22.619 30.159]'; % feedrate for 3600 rpm
    %Feed=[8.378 16.755 25.133 33.510]'; % feedrate for 4000 rpm
elseif j==5
    disp('Half Immersion Up Milling');
    enter=0;
    exit=1/2*pi;
    Theta=1/2*pi;
    RD=1/2*D; % radial depth half immersion unit: inch
    Feed=[0.942 1.885 2.827 3.770]'; % feedrate for 600 rpm unit: inch/min
    %Feed=[4.712 9.425 14.137 18.850]'; % feedrate for 3000 rpm
    %Feed=[5.655 11.310 16.965 22.619]'; % feedrate for 3600 rpm
    %Feed=[6.283 12.566 18.850 25.133]'; % feedrate for 4000 rpm
elseif j==6
    disp('Three Quarter Immersion Up Milling');
    enter=0;
    exit=2/3*pi;
    Theta=2/3*pi;
    RD=3/4*D; % radial depth three quarter immersion unit: inch
    Feed=[0.838 1.676 2.513 3.351]'; % feedrate for 600 rpm unit: inch/min
    %Feed=[4.189 8.378 12.566 16.755]'; % feedrate for 3000 rpm
    %Feed=[5.027 10.053 15.080 20.106]'; % feedrate for 3600 rpm
    %Feed=[5.585 11.170 16.755 22.340]'; % feedrate for 4000 rpm
end

figure
strain_data=[s(i:end),s(1:i-1)];
plot(strain_time,strain_data);
title('Strain Data from Smart Tool');
xlabel('Time (s)');
ylabel('Strain (bit)');

% calculate the zero offset of smart tool
num1=cursor_info_0.DataIndex;
num2=cursor_info_00.DataIndex;
zerobit=mean(strain_data(num1:num2))
strain=strain_data-zerobit;
Ft_data=strain/1.64*4.448222; % unit:N
figure
plot(strain_time,Ft_data);
title('Raw Force from Smart Tool');
xlabel('Time (s)');
ylabel('Ft (N)');

% Find the tangential force for the first feedrate used for calibration
cycles=20; % use 20 cycles of data to get the average
number=floor(60/rpm*fs); % how many samples collected in one cycle
startnum=cursor_info_1.DataIndex;
endnum=startnum+number*cycles-1;
time=strain_time(startnum:endnum);
Ft_raw=Ft_data(startnum:endnum);
figure
plot(time,Ft_raw);
Ft(1)=mean(Ft_raw);

% Find the tangential force for the second feedrate used for calibration
startnum=cursor_info_2.DataIndex;
endnum=startnum+number*cycles-1;
time=strain_time(startnum:endnum);
Ft_raw=Ft_data(startnum:endnum);
figure
plot(time,Ft_raw);
Ft(2)=mean(Ft_raw);

% Find the tangential force for the third feedrate used for calibration
startnum=cursor_info_3.DataIndex;
endnum=startnum+number*cycles-1;
time=strain_time(startnum:endnum);
Ft_raw=Ft_data(startnum:endnum);
figure
plot(time,Ft_raw);
Ft(3)=mean(Ft_raw);

% Find the tangential force for the fourth feedrate used for calibration
startnum = cursor_info_4.DataIndex;
endnum = startnum + number * cycles - 1;
time = strain_time(startnum:endnum);
Ft_raw = Ft_data(startnum:endnum);
figure
plot(time, Ft_raw);
Ft (4) = mean(Ft_raw);

%%
%% Tangential coefficients calibration
if j<4
    for i=1:4
        fp(i) = Feed(i) / (N*rpm);
        Gtc(i) = -25.4^2 * N * AD * fp(i) / (2*pi) * (cos(exit) - cos(enter));
        Gte(i) = 25.4 * N * AD / (2*pi) * (exit - enter);
    end
else
    for i=1:4
        fp(i) = Feed(i) / (N*rpm_avg);
        fp(i) = Feed(i) / (N*rpm);
        Gtc(i) = -25.4^2 * N * AD * fp(i) / (2*pi) * (cos(exit) - cos(enter));
        Gte(i) = 25.4 * N * AD / (2*pi) * (exit - enter);
    end
end
G = [Gtc(1) Gte(1); Gtc(2) Gte(2); Gtc(3) Gte(3); Gtc(4) Gte(4)];

if k==1
    Ft = [Ft(1); Ft(2); Ft(3); Ft(4)];
    disp('Tangential coefficients: Ktc and Kte');
    Kt = inv(G'*G)*G'*Ft
else
    Fr = [Ft(1); Ft(2); Ft(3); Ft(4)];
    disp('Radial coefficients: Krc and Kre');
    Kr = inv(G'*G)*G'*Fr
end

**Force Model Calibration Using Kistler Force Profile**

% This program can only be used in up milling
% Using the cutting force profile measured from Kistler to calibrate
% the cutting coefficients
% Considering the helix angle but ignoring tool dynamics effect while
% calculating instantaneous chip thickness
% Using the integration idea and least squares to get the cutting
% coefficients
% Coordinates have been changed to make the radial immersion angle
% starting
% from 0, thus the final equations should be the same as the equations
% shown on Page 44 of Altintas's book.
% Input: cutting geometry and measured data file for Kistler
% Output: cutting coefficients calibrated from the Kistler force
% profile method

% By Yong Zhao
% Revised on April 06 2012
% Design and Manufacturing Lab, University of New Hampshire

clear all;

rpm=3000;
s=18000;  % Sampling frequency
fs=7200;
numpercycle=floor(60*fs/rpm);
cycles=20;  % number of cycles of force to be used

%%
% Input related parameters

N=1;  % number of tooth
AD=0.125*25.4;  % axial depth : mm
D=0.75*25.4;  % diameter of the tool : mm
beta=14.73/180*pi;  % helix angle in radians

if i==4
    enter=0;
    exit=1/3*pi;
    Feed=[1.257 2.513 3.770 5.027]';  % feedrate for 600 rpm
    unit:inch/min
    Feed=[6.283 12.566 18.850 25.133]';  % feedrate for 3000 rpm
    Feed=[7.540 15.080 22.619 30.159]';  % feedrate for 3600 rpm
    Feed=[8.378 16.755 25.133 33.510]';  % feedrate for 4000 rpm
elseif i==5
    enter=0;
    exit=1/2*pi;
    Feed=[0.942 1.885 2.827 3.770]';  % feedrate for 600 rpm
    unit:inch/min
    Feed=[5.655 11.310 16.965 22.619]';  % feedrate for 3600 rpm
    Feed=[6.283 12.566 18.850 25.133]';  % feedrate for 4000 rpm
elseif i==6
    enter=0;
    exit=2/3*pi;
    Feed=[0.838 1.676 2.513 3.351]';  % feedrate for 600 rpm
    unit:inch/min
    Feed=[4.189 8.378 12.566 16.755]';  % feedrate for 3000 rpm
    Feed=[5.027 10.053 15.080 20.106]';  % feedrate for 3600 rpm
clear Fx_new Fy_new tick_new;

%% Get the correct data file
% Single data file
[fileName,PathName,FilterIndex] = uigetfile('*.csv', 'Please choose an excel file');
if( fileName == 0 )
    return;
end;
fname = sprintf('%s%s', PathName, fileName)
[a b c]=xlsread(fname);

% Multiple data files
a=[];
Nfiles=2;
filename='Aluminum3k36k4kQuarterUpTangential';
for n = 1:Nfiles
    % Name of sub-file to read
    namespace = strcat(filename,int2str(n-1)','.csv');
    % Read xls data
    [newdata, headertext] = xlsread(namespace);
    % Concatenate data
    a = vertcat(a,newdata);
end

%% Plot raw Fx and Fy from Kistler
figure
subplot(2,1,1)
plot(a(:,1),-a(:,2));
title('Raw Force Data from Kistler in X Direction');
xlabel('Time (s)');
ylabel('Fx (volt)');

subplot(2,1,2)
plot(a(:,1),-a(:,3));
title('Raw Force Data from Kistler in Y Direction');
xlabel('Time (s)');
ylabel('Fy (volt)');

% plot raw Fx
num1=cursor_info_0.DataIndex;
num2=cursor_info_00.DataIndex;
disp('Kistler zero offset at X and Y direction in the end');
Fx_zero_offset=mean(a(num1:num2,2))
Fy_zero_offset=mean(a(num1:num2,3))
a(:,2)=a(:,2)-Fx_zero_offset;
a(:,3)=a(:,3)-Fy_zero_offset;
Fx_all=-500*a(:,2);
Fy_all=-500*a(:,3);
tick_all=100*a(:,6);
figure
% plot(a(:,1),Fx_all,a(:,1),tick_all);
plot(a(:,1),Fy_all)
title('Raw Force Data from Kistler in Y Direction');
xlabel('Time (s)');
ylabel('Fy (N)');

%%
% Get 20 cycles of force data for the selected feedrate

startnum=cursor_info_l.DataIndex;
endnum=startnum+numpercycle*cycles-1;
time=(linspace(0,60/(rpm*numpercycle)*(numpercycle*cycles-1),numpercycle*cycles));
time_one=(linspace(0,60/(rpm*numpercycle)*(numpercycle-1),numpercycle))';
Fx=Fx_all(startnum:endnum);
Fy=Fy_all(startnum:endnum);
tick=tick_all(startnum:endnum);
figure;
plot(time,Fx,time,tick)

%%
% find the first trigger point of each cycle of tick signal to calculate
% the actual spindle speed and be as the reference position for later calibration
for i=1:cycles
    tickout=tick(1+numpercycle*(i-1):numpercycle*i);
    tickoutnum=find(tickout<10);
    ticknum(i)=min(tickoutnum)+numpercycle*(i-1);
end
hold on;
plot(time(ticknum),tick(ticknum),'ro');
for i=1:cycles-1
    rpm_ins(i)=60*fs/(ticknum(i+1)-ticknum(i));
end
rpm_avg=19*60*fs/(ticknum(cycles)-ticknum(1))
% Align the 20 cycles of raw force data and average them to get one cycle of raw force data

for i=1:cycles
    Fx_new(i,:) = Fx(1+numpercycle*(i-1):numpercycle*i);
    Fy_new(i,:) = Fy(1+numpercycle*(i-1):numpercycle*i);
    tick_new(i,:) = tick(1+numpercycle*(i-1):numpercycle*i);
end

figure
subplot(2,2,1);
plot(time_one,Fx_new);
title('Unshifted Fx');
xlabel('Time (s)');
ylabel('Fx (N)');
ylim([-250 50])

subplot(2,2,2);
plot(time_one,Fy_new);
title('Unshifted Fy');
xlabel('Time (s)');
ylabel('Fy (N)');
ylim([-100 150])

% Shift and align the 20 cycles of the raw force data

for i=1:cycles
    [magx,idx] = max(xcorr(Fx_new(1,:),Fx_new(i,:),numpercycle));
    Fx_new(i,:) = circshift(Fx_new(i,:),[0,idx-numpercycle-1]);
    Fy_new(i,:) = circshift(Fy_new(i,:),[0,idx-numpercycle-1]);
end

% Plot the shifted raw data
hold on;
subplot(2,2,3);
plot(time_one,Fx_new);
title('Shifted Fx');
xlabel('Time (s)');
ylabel('Fx (N)');
ylim([-250 50])

subplot(2,2,4);
plot(time_one,Fy_new);
title('Shifted Fy');
xlabel('Time (s)');
ylabel('Fy (N)');
% Average to get one cycle of raw force data
Fx_one=mean(Fx_new);
Fy_one=mean(Fy_new);
Fres=sqrt(Fx_one.^2+Fy_one.^2); % Calculate the raw resultant force

figure
plot(time_one, Fx_one);
xlabel('Time (s)');
ylim([-100 150]);
figure
plot(time_one, Fy_one);
xlabel('Time (s)');
ylabel('Fy (N)');
ylim([-100 150]);

figure;
[AX, H1, H2] = plotyy(time_one, Fx_one, time_one, tick(1:numpercycle)/100, 'plot');
set(get(AX(1), 'Ylabel'), 'String', 'Force (N) ')
set(get(AX(2), 'Ylabel'), 'String', 'Tick Signal (Volts)')
set(AX(1), 'ylim', [-500 500]);
set(AX(2), 'ylim', [-5 5]);
xlabel('Time (s)');
hold on;
plot(time_one, Fy_one, 'g')
legend('Averaged Fx', 'Averaged Fy', 'Tick Signal');
set(AX, {'ycolor'}, {'k'; 'r'})
clear Fxc Fyc A1x A2x A3x A4x A1y A2y A3y A4y;

ft=Feed(4)*25.4/rpm/N; % feed per tooth : mm/tooth
degree=1/fs*rpm*360/60;
alpha=-94/180*pi;
startnum=ticknum(1);
endnum=numpercycle;
delta=10/180*pi; % angle used to subtract from the enter-exit range to
% narrow the range to do calibration
lag=2*AD*tan(beta)/D;
n=1;
for j=1:endnum-startnum+1
    index=j+startnum-1;
    theta=alpha+degree*(j-1)/180*pi;
    if (theta<=exit-delta) && (theta>=enter+delta)
\[
\text{thetal} = \theta; \\
\text{theta2} = \theta - \text{lag}; \\
Fxc(n) = Fx\_one(index); \\
Fyc(n) = Fy\_one(index); \\
\]

\[
A1x(n) = -1/4*\text{ft}*(\cos(2*\text{theta2}) - \cos(2*\text{thetal})); \\
A2x(n) = \sin(\text{theta2}) - \sin(\text{thetal}); \\
A3x(n) = 1/4*\text{ft}*(2*(\text{theta2} - \text{thetal}) - (\sin(2*\text{theta2}) - \sin(2*\text{thetal}))); \\
A4x(n) = -(\cos(\text{theta2}) - \cos(\text{thetal})); \\
\]

\[
A1y(n) = -1/4*\text{ft}*(2*(\text{theta2} - \text{thetal}) - (\sin(2*\text{theta2}) - \sin(2*\text{thetal}))); \\
A2y(n) = \cos(\text{theta2}) - \cos(\text{thetal}); \\
A3y(n) = -1/4*\text{ft}*(\cos(2*\text{theta2}) - \cos(2*\text{thetal})); \\
A4y(n) = \sin(\text{theta2}) - \sin(\text{thetal}); \\
\]

\[n = n + 1;\]
end

\[
Mx = [A1x' A2x' A3x' A4x']; \\
My = [A1y' A2y' A3y' A4y']; \\
Fxc\_cali = Fxc'; \\
Fyc\_cali = Fyc'; \\
Mxy = \text{cat}(1, Mx, My); \\
Fxy = \text{cat}(1, Fx\_cali, Fy\_cali); \\
\]

\[
Kxy = 2*\tan(\beta)/D*\text{inv}(Mxy'*Mxy)*Mxy'*Fxy \\
\]

**Force Model Calibration Using Smart Tool Force Profile**

This program can only be used in up milling

Using the cutting force profile measured from Smart Tool to calibrate the

cutting coefficients

Coordinates have been changed to make the radial immersion angle starting from 0

Input: cutting geometry and measured data file for Smart Tool

Output: cutting coefficients calibrated from the Smart Tool force profile method

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February 20 2012

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clc;
close all;
clear all;

figure
strain_data=[s(i:end),s(1:i-1)];
plot(strain_time,strain_data);
title('Strain Data from Smart Tool');
xlabel('Time (s)');
ylabel('Strain (bit)');

rpm=3000;
fs=10240;
umpercycle=floor(60*fs/rpm);
cycles=20; % number of cycles of force to be used

N=1; % number of tooth
AD=0.125; % axial depth unit:inch
D=0.75; % diameter of the tool unit: inch
beta=14.73/180*pi;
lag=2*AD*tan(beta)/D;

k=1; % k=1 tangential coefficients calibration; k=2 radial coefficients calibration
j=4; % j=1, 2 and 3 means down milling 1/4 immersion, 1/2 immersion and 3/4 immersion; j=4, 5 and 6 means up milling 1/4 immersion, 1/2 immersion and 3/4 immersion.

if j==1
    disp('Quarter Immersion Down Milling');
    enter=2/3*pi;
    exit=pi;
    Theta=1/3*pi;
    RD=1/4*D; % radial depth quarter immersion unit: inch
    Feed=[5.445 10.891 16.336 21.782]'; % feedrate unit:inch/min
elseif j==2
    disp('Half Immersion Down Milling');
    enter=1/2*pi;
    exit=pi;
    Theta=1/2*pi;
    RD=1/2*D; % radial depth half immersion unit: inch
    Feed=[4.084 8.168 12.252 16.336]'; % feedrate unit:inch/min
elseif j==3
    disp('Three Quarter Immersion Down Milling');
    enter=1/3*pi;
    exit=pi;
    Theta=2/3*pi;
    RD=3/4*D; % radial depth three quarter immersion unit: inch
    Feed=[3.63 7.261 10.891 14.521]'; % feedrate unit:inch/min
else if j==4
    disp('Quarter Immersion Up Milling');
    enter=0;
    exit=1/3*pi;
    Theta=1/3*pi;
    RD=1/4*D; % radial depth quarter immersion unit: inch
    % Feed=[1.257 2.513 3.770 5.027]'; % feedrate for 600 rpm
    % Feed=[6.283 12.566 18.850 25.133]'; % feedrate for 3000 rpm
    % Feed=[7.540 15.080 22.619 30.159]'; % feedrate for 3600 rpm
    % Feed=[8.378 16.755 23.133 33.510]'; % feedrate for 4000 rpm
else if j==5
    disp('Half Immersion Up Milling');
    enter=0;
    exit=1/2*pi;
    Theta=1/2*pi;
    RD=1/2*D; % radial depth half immersion unit: inch
    Feed=[0.942 1.885 2.827 3.770]'; % feedrate for 600 rpm
    % Feed=[4.712 9.425 14.137 18.850]'; % feedrate for 3000 rpm
    % Feed=[5.655 11.310 16.965 22.619]'; % feedrate for 3600 rpm
    % Feed=[6.283 12.566 18.850 25.133]'; % feedrate for 4000 rpm
else if j==6
    disp('Three Quarter Immersion Up Milling');
    enter=0;
    exit=2/3*pi;
    Theta=2/3*pi;
    RD=3/4*D; % radial depth three quarter immersion unit: inch
    Feed=[0.838 1.676 2.513 3.351]'; % feedrate for 600 rpm
    % Feed=[4.189 8.378 12.566 16.755]'; % feedrate for 3000 rpm
    % Feed=[5.027 10.053 15.080 20.106]'; % feedrate for 3600 rpm
    % Feed=[5.585 11.170 16.755 22.340]'; % feedrate for 4000 rpm
end

% calculate the zero offset of smart tool
num1=cursor_info_0.DataIndex;
num2=cursor_info_00.DataIndex;
zerobit=mean(strain_data(num1:num2));
strain=strain_data-zerobit;
Ft_data=strain/1.64*4.448222; % unit:N
figure
plot(strain_time,Ft_data);
title('Raw Force from Smart Tool');
xlabel('Time (s)');
ylabel('Ft (N)');

% Find the tangential force for the first feedrate used for calibration
startnum=cursor_info_1.DataIndex;
endnum=startnum+numpercycle*cycles-1;

endnum=strain_time(startnum:endnum);
time=(linspace(0,60/(rpm*numpercycle)*(numpercycle*cycles-1),numpercycle*cycles));

time_one=(linspace(0,60/(rpm*numpercycle)*(numpercycle-1),numpercycle))';

Ft_raw=Ft_data(startnum:endnum);
figure
plot(time,Ft_raw);
xlabel('Time (s)');
ylabel('Ft (N) ' );
% ylim([-20 90]);

%% FFT of the chose 20 cycles of tangential or radial force

NFFT=numpercycle*cycles;
n=floor(NFFT/2+1);
for i=1:n
    f(i)=(i-1)*fs/NFFT;
end

w = hann(NFFT);
g1 = (Ft_raw-mean(Ft_raw))';

Ft_fft = fft(g1.*w,NFFT)/NFFT;
figure
stem(f,2*abs(Ft_fft(1:n)),'*');
% title('Single-Sided Amplitude Spectrum of Ft')
xlim([0 2000])
xlabel('Frequency (Hz)')
ylabel('|Fr| (N)')

%%

for i=1:cycles
    Ft_raw_new(i,:)=Ft_raw(1+numpercycle*(i-1):numpercycle*i);
end

figure
plot(time_one,Ft_raw_new);
% title('Unshifted Ft');
xlabel('Time (s)');
ylabel('Fr (N) ' );
% Shift and align the 20 cycles of the raw force data

for i=1:cycles
    [magFt idFt] =
    max(xcorr(Ft_raw_new(1,:),Ft_raw_new(i,:),numpercycle));
    Ft_raw_new(i,:) = circshift(Ft_raw_new(i,:),[0,idFt-numpercycle-1]);
end
% Plot the shifted raw data
figure;
plot(time_one, Ft_raw_new);
% title('Shifted Ftraw');
xlabel('Time (s)');
ylabel('Fr (N)');
% ylim([-20 90]);
% Average to get one cycle of raw force data
Ft_raw_one=mean(Ft_raw_new);

figure
plot(time_one,Ft_raw_one);
xlabel('Time (s)');
ylabel('Fr (N)');

startnum=cursor_info_a.DataIndex;

%%
% Cutting coefficients calibration
ft=Feed(4)*25.4/rpm/N; % feed per tooth : mm/tooth
alpha=0;
degree=1/fs*rpm*360/60;
delta=10/180*pi; % angle used to subtract from the enter-exit range to
% narrow the range to do calibration
n=1;
for j=1:floor(((Theta+lag)*numpercycle/2/pi)
  index=j+startnum-1;
  theta=(alpha+degree*(j-1))/180*pi;
  if (theta<=exit-delta) && (theta>=enter+delta)
    Ft_cali(n)=Ft_raw_one(index);
    h(n)=ft*sin(theta-1/2*lag);
    n=n+1;
  end
end

%%
if k==1
  disp('Tangential coefficients: Ktc and Kte');
  Kt=polyfit(h,Ft_cali/(AD*25.4),1)
else
  disp('Radial coefficients: Krc and Kre');
  Kr=polyfit(h,Ft_cali/(AD*25.4),1)
end

figure;
plot(h,Ft_cali/(AD*25.4),'*');
xlabel('Instantaneous Chip Thickness h: mm');
ylabel('Ft/a: N/mm')
Resultant Force Simulation and Comparison

% Simulate resultant cutting force by using coefficients obtained from
% each calibration method
% This program can only be used in up milling
% Considering the helix angle but ignoring tool dynamics effect while
% calculating instantaneous chip thickness
% Coordinates have been changed to make the radial immersion angle
% starting from 0

% Input: cutting geometry, obtained cutting coefficients from each
% calibration method and measured data file for Kistler
% Output: Fx, Fy and resultant force simulated based on the input and
% the relative error of the peak resultant force between the simulated
% and the Kistler measured

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% Revised on April 08 2012
% Design and Manufacturing Lab, University of New Hampshire

cclc;
close all;
clear all;

%%
rpm=3000;
fs=18000; % Sampling frequency for 3000 RPM
fs=7200; % Sampling frequency for 600 RPM
numpercycle=floor(60*fs/rpm);
cycles=20; % number of cycles of force to be used

% the following ratios have been checked and confirmed
% ratio1=[0.3686 0.5623]; % ratio from 600 RPM cutting tests
ratio1=[0.3959 0.6301]; % ratio from 3000 RPM cutting tests
ratio2=[0.3822 0.5962]; % ratio from the combined data

%%
% Input related parameters

N=1; % number of tooth
AD=0.125*25.4; % axial depth : mm
D=0.75*25.4; % diameter of the tool : mm
beta=14.73/180*pi; % helix angle in radians

i=6; % i=4,5,6 means quarter, half and three quarter immersion in up
milling;
if i==4
    enter=0;
    exit=1/3*pi;
    Feed=[1.257 2.513 3.770 5.027]'; % feedrate for 600 rpm

unit:inch/min
Feed=[6.283 12.566 18.850 25.133]'; % feedrate for 3000 rpm
% Feed=[7.540 15.080 22.619 30.159]'; % feedrate for 3600 rpm
% Feed=[8.378 16.755 25.133 33.510]'; % feedrate for 4000 rpm
elseif i==5
    enter=0;
    exit=0.5*pi;
    % Feed=[0.942 1.835 2.827 3.770]'; % feedrate for 600 rpm
unit:inch/min
% Feed=[5.655 11.310 16.965 22.619]'; % feedrate for 3600 rpm
% Feed=[6.203 12.566 18.850 25.133]'; % feedrate for 4000 rpm
elseif i==6
    enter=0;
    exit=2/3*pi;
% Feed=[0.838 1.676 2.513 3.351]'; % feedrate for 600 rpm
unit:inch/min
    Feed=[4.189 8.378 12.566 16.755]'; % feedrate for 3000 rpm
% Feed=[5.027 10.053 15.080 20.106]'; % feedrate for 3600 rpm
% Feed=[5.585 11.170 16.755 22.340]'; % feedrate for 4000 rpm
end

clear Fx_new Fy_new tick_new;

% Get the correct data file
% Single data file
% [fileName,PathName,FilterIndex] = uigetfile('*.*','.csv', 'Please choose an excel file');
% if( fileName == 0 )
%     return;
% end;
% fname = sprintf('%s%s', PathName, fileName)
% [a b c]=xlsread(fname);

% Multiple data files
a=[];
Nfiles=2;
filename='Aluminum3k36k4kThreeQuarterUpTangential';
for n = 1:Nfiles
    % Name of sub-file to read
    namespace = strcat(filename,int2str(n-1),'.csv');
    % Read xls data
    [newdata, headertext] = xlsread(namespace);
    % Concatenate data
    a = vertcat(a,newdata);
end

% Plot raw Fx and Fy from Kistler

- 125 -
figure
subplot(2,1,1)
plot(a(:,1),-a(:,2));
title('Raw Force Data from Kistler in X Direction');
xlabel('Time (s)');
ylabel('Fx (volt)');

subplot(2,1,2)
plot(a(:,1),-a(:,3));
title('Raw Force Data from Kistler in Y Direction');
xlabel('Time (s)');
ylabel('Fy (volt)');

% plot raw Fx
num1=cursor_info_0.DataIndex;
num2=cursor_info_00.DataIndex;
disp('Kistler zero offset at X and Y direction in the end');
Fx_zero_offset=mean(a(num1:num2,2))
Fy_zero_offset=mean(a(num1:num2,3))

a(:,2)=a(:,2)-Fx_zero_offset;
a(:,3)=a(:,3)-Fy_zero_offset;
Fx_all=-500*a(:,2);
Fy_all=-500*a(:,3);
tick_all=100*a(:,6);
figure
% plot(a(:,1),Fx_all,a(:,1),tick_all);
plot(a(:,1),Fy_all)
title('Raw Force Data from Kistler in Y Direction');
xlabel('Time (s)');
ylabel('Fy (N)');

% Get 20 cycles of force data for the selected feedrate
startnum=cursor_info_3.DataIndex;
endnum=startnum+numpercycle*cycles-1;
time=(linspace(0,60/(rpm*numpercycle)*(numpercycle*cycles-1),numpercycle*cycles));
time_one=(linspace(0,60/(rpm*numpercycle)*(numpercycle-1),numpercycle));
Fx=Fx_all(startnum:endnum);
Fy=Fy_all(startnum:endnum);
tick=tick_all(startnum:endnum);
figure;
plot(time,Fx,time,tick)
% find the first trigger point of each cycle of tick signal to
calculate the actual spindle speed and be as the reference position

for i=1:cycles
    tickout=tick(1+numpercycle*(i-1):numpercycle*i);
    tickoutnum=find(tickout<10);
    ticknum(i)=min(tickoutnum)+numpercycle*(i-1);
end

hold on;
plot(time(ticknum),tick(ticknum),'ro');
for i=1:cycles-1
    rpm_ins(i)=60*fs/(ticknum(i+1)-ticknum(i));
end

rpm_avg=19*60*fs/(ticknum(cycles)-ticknum(1))

%%
% Align the 20 cycles of raw force data and average them to get one
% cycle of raw force data

for i=1:cycles
    Fx_new(i,:)=Fx(1+numpercycle*(i-1):numpercycle*i);
    Fy_new(i,:)=Fy(1+numpercycle*(i-1):numpercycle*i);
    tick_new(i,:)=tick(1+numpercycle*(i-1):numpercycle*i);
end

figure
subplot(2,2,1);
plot(time_one,Fx_new);
title('Unshifted Fx');
xlabel('Time (s)');
ylabel('Fx (N)');
ylim([-250 50])

subplot(2,2,2);
figure;
plot(time_one,Fy_new);
title('Unshifted Fy');
xlabel('Time (s)');
ylabel('Fy (N)');
ylim([-100 150])

%%
% Shift and align the 20 cycles of the raw force data

for i=1:cycles
    [magx idx] = max(xcorr(Fx_new(i,:),Fx_new(i,:),numpercycle));
    Fx_new(i,:)=circshift(Fx_new(i,:),[0,idx-numpercycle-1]);
    Fy_new(i,:)=circshift(Fy_new(i,:),[0,idx-numpercycle-1]);
end
% Plot the shifted raw data
hold on;
subplot(2,2,3);
% figure;
plot(time_one,Fx_new);
title('Shifted Fx');
xlabel('Time (s)');
ylabel('Fx (N)');
ylim([-250 50]);

subplot(2,2,4);
% figure;
plot(time_one,Fy_new);
title('Shifted Fy');
xlabel('Time (s)');
ylabel('Fy (N)');
ylim([-100 150]);

% Average to get one cycle of raw force data
Fx_one=mean(Fx_new);
Fy_one=mean(Fy_new);
Fres=sqrt(Fx_one.^2+Fy_one.^2); % Calculate the raw resultant force

%%
ft=Feed(3)*25.4/rpm/N; % feed per tooth : mm/tooth
degree=1/fs*rpm*360/60;
startnum=ticknum(1);

%%
clear Fx_est Fy_est;

%%
% Using the Kistler Average Force Based Cutting Coefficients to
% simulate the Instantaneous Cutting Force
L=100;

Ktc=656.8417; % unit: N/mm^2
Kte=19.6580; % unit: N/mm
Krc=301.1310; % unit: N/mm^2
Kre=11.2332; % unit: N/mm

alpha=-94-(startnum-1)*degree;
for j=1:numpercycle
    theta=(alpha+degree*(j-1))/180*pi;
    if (theta>enter) && ((theta-2*AD*tan(beta)/D)<=enter)
        Fx_est(j)=0;
        Fy_est(j)=0;
        for k=1:L
            theta2=theta-2*tan(beta)/D*AD/L*k;
            if (theta2>enter)
                dFt=(Ktc*ft*sin(theta2)+Kte)*AD/L;
                dFr=(Krc*ft*sin(theta2)+Kre)*AD/L;
            else
                dFt=0;
                dFr=0;
            end
        end
    else
        Fx_est(j)=Fx_one;
        Fy_est(j)=Fy_one;
    end
end

% Calculate the resultant force
Fx_est=mean(Fx_est);
Fy_est=mean(Fy_est);
Fres=sqrt(Fx_est.^2+Fy_est.^2);

% Plot the estimated cutting force
hold on;
subplot(2,2,3);
% figure;
plot(time_one,Fx_est);
title('Estimated Fx');
xlabel('Time (s)');
ylabel('Fx (N)');
ylim([-250 50]);

subplot(2,2,4);
% figure;
plot(time_one,Fy_est);
title('Estimated Fy');
xlabel('Time (s)');
ylabel('Fy (N)');
ylim([-100 150]);
dFx=-dFt*cos(theta2)-dFr*sin(theta2);
dFy=dFt*sin(theta2)-dFr*cos(theta2);
Fx_est(j)=Fx_est(j)+dFx;
Fy_est(j)=Fy_est(j)+dFy;
else
    break;
end
elseif (theta<=exit) && ((theta-2*AD*tan(beta)/D)>=enter)
    Fx_est(j)=0;
    Fy_est(j)=0;
for k=1:L
    theta2=theta-2*tan(beta)/D*AD/L*k;
    dFt=(Ktc*ft*sin(theta2)+Kte)*AD/L;
    dFr=(Krc*ft*sin(theta2)+Kre)*AD/L;
    dFx=-dFt*cos(theta2)-dFr*sin(theta2);
    dFy=dFt*sin(theta2)-dFr*cos(theta2);
    Fx_est(j)=Fx_est(j)+dFx;
    Fy_est(j)=Fy_est(j)+dFy;
end
elseif (theta>exit) && ((theta-2*AD*tan(beta)/D)<exit)
    Fx_est(j)=0;
    Fy_est(j)=0;
for k=1:L
    theta2=theta-2*tan(beta)/D*AD/L*k;
    if (theta2<=exit)
        dFt=(Ktc*ft*sin(theta2)+Kte)*AD/L;
        dFr=(Krc*ft*sin(theta2)+Kre)*AD/L;
        dFx=-dFt*cos(theta2)-dFr*sin(theta2);
        dFy=dFt*sin(theta2)-dFr*cos(theta2);
        Fx_est(j)=Fx_est(j)+dFx;
        Fy_est(j)=Fy_est(j)+dFy;
    else
        theta1=theta2;
    end
else
    Fx_est(j)=0;
    Fy_est(j)=0;
end
end

Fx_kistler_avg=Fx_est;
Fy_kistler_avg=Fy_est;
Fres_kistler_avg=sqrt(Fx_kistler_avg.^2+Fy_kistler_avg.^2);

% Using the Smart Tool Average Force Based Cutting Coefficients to
% simulate the Instantaneous Cutting Force

Ktc=761.5866; % unit: N/mm^2
Kte=17.8042; % unit: N/mm
Krc=233.5516; % unit: N/mm^2
Kre=13.0211; \text{ unit: N/mm}

for j=1:numpercycle
    theta=(alpha+degree*(j-1))/180*pi;
    if (theta>enter) \&\& ((theta-2*AD*tan(beta)/D)<enter)
        Fx_est(j)=0;
        Fy_est(j)=0;
    for k=1:L
        theta2=theta-2*tan(beta)/D*AD/L*k;
        if (theta2>=enter)
            dFt=(Ktc*ft*sin(theta2)+Kte)*AD/L;
            dFr=(Krc*ft*sin(theta2)+Kre)*AD/L;
            dFx=-dFt*cos(theta2)-dFr*sin(theta2);
            dFy=dFt*sin(theta2)-dFr*cos(theta2);
            Fx_est(j)=Fx_est(j)+dFx;
            Fy_est(j)=Fy_est(j)+dFy;
        else
            break;
        end
    end
    elseif (theta<=exit) \&\& ((theta-2*AD*tan(beta)/D)>=enter)
        Fx_est(j)=0;
        Fy_est(j)=0;
    for k=1:L
        theta2=theta-2*tan(beta)/D*AD/L*k;
        dFt=(Ktc*ft*sin(theta2)+Kte)*AD/L;
        dFr=(Krc*ft*sin(theta2)+Kre)*AD/L;
        dFx=-dFt*cos(theta2)-dFr*sin(theta2);
        dFy=dFt*sin(theta2)-dFr*cos(theta2);
        Fx_est(j)=Fx_est(j)+dFx;
        Fy_est(j)=Fy_est(j)+dFy;
    end
    elseif (theta>exit) \&\& ((theta-2*AD*tan(beta)/D)<exit)
        Fx_est(j)=0;
        Fy_est(j)=0;
    for k=1:L
        theta2=theta-2*tan(beta)/D*AD/L*k;
        if (theta2<=exit)
            dFt=(Ktc*ft*sin(theta2)+Kte)*AD/L;
            dFr=(Krc*ft*sin(theta2)+Kre)*AD/L;
            dFx=-dFt*cos(theta2)-dFr*sin(theta2);
            dFy=dFt*sin(theta2)-dFr*cos(theta2);
            Fx_est(j)=Fx_est(j)+dFx;
            Fy_est(j)=Fy_est(j)+dFy;
        else
            theta1=theta2;
        end
    end
else
    Fx_est(j)=0;
    Fy_est(j)=0;
end
end
Fx_ST_avg=Fx_est;
Fy_ST_avg=Fy_est;
Fres_ST_avg=sqrt(Fx_ST_avg.^2+Fy_ST_avg.^2);

%%
%% Using ratio1 to simulate the Instantaneous Cutting Force

Ktc=738.6378  % unit: N/mm^2
Kte=13.8394  % unit: N/mm

disp('Radial Cutting Coefficients obtained from Ratio 1');
Krc=Ktc*ratiol(1)  % unit: N/mm^2
Kre=Kte*ratiol(2)  % unit: N/mm

for j=1:numpercycle
    theta=(alpha+degree*(j-1))/180*pi;
    if (theta>enter) && ((theta-2*AD*tan(beta)/D)<=enter)
        Fx_est(j)=0;
        Fy_est(j)=0;
        for k=1:L
            theta2=theta-2*tan(beta)/D*AD/L*k;
            if (theta2>=enter)
                dFt=(Ktc*ft*sin(theta2)+Kte)*AD/L;
                dFr=(Krc*ft*sin(theta2)+Kre)*AD/L;
                dFx=-dFt*cos(theta2)-dFr*sin(theta2);
                dFy=dFt*sin(theta2)-dFr*cos(theta2);
                Fx_est(j)=Fx_est(j)+dFx;
                Fy_est(j)=Fy_est(j)+dFy;
            else
                break;
            end
        end
    elseif (theta<=exit) && ((theta-2*AD*tan(beta)/D)>=enter)
        Fx_est(j)=0;
        Fy_est(j)=0;
        for k=1:L
            theta2=theta-2*tan(beta)/D*AD/L*k;
            if (theta2<=exit)
                dFt=(Ktc*ft*sin(theta2)+Kte)*AD/L;
                dFr=(Krc*ft*sin(theta2)+Kre)*AD/L;
                dFx=-dFt*cos(theta2)-dFr*sin(theta2);
                dFy=dFt*sin(theta2)-dFr*cos(theta2);
                Fx_est(j)=Fx_est(j)+dFx;
                Fy_est(j)=Fy_est(j)+dFy;
            else
                break;
            end
        end
    elseif (theta>exit) && ((theta-2*AD*tan(beta)/D)<exit)
        Fx_est(j)=0;
        Fy_est(j)=0;
        for k=1:L
            theta2=theta-2*tan(beta)/D*AD/L*k;
            if (theta2<exit)
                dFt=(Ktc*ft*sin(theta2)+Kte)*AD/L;
                dFr=(Krc*ft*sin(theta2)+Kre)*AD/L;
                dFx=-dFt*cos(theta2)-dFr*sin(theta2);
                dFy=dFt*sin(theta2)-dFr*cos(theta2);
                Fx_est(j)=Fx_est(j)+dFx;
                Fy_est(j)=Fy_est(j)+dFy;
            end
        end
end

Fx_ST_avg=Fx_est;
Fy_ST_avg=Fy_est;
Fres_ST_avg=sqrt(Fx_ST_avg.^2+Fy_ST_avg.^2);
\[
\begin{align*}
\text{dFx} &= -\text{dFt} \cos(\theta_2) - \text{dFr} \sin(\theta_2); \\
\text{dFy} &= \text{dFt} \sin(\theta_2) - \text{dFr} \cos(\theta_2); \\
\text{Fx}_{\text{est}}(j) &= \text{Fx}_{\text{est}}(j) + \text{dFx}; \\
\text{Fy}_{\text{est}}(j) &= \text{Fy}_{\text{est}}(j) + \text{dFy}; \\
\text{else} & \text{ \{ otherwise \} } \\
\theta_{\text{tal}} &= \theta_2; \\
\text{end} \\
\text{end} \\
\text{end} \\
\text{else} & \text{ \{ otherwise \} } \\
\text{Fx}_{\text{est}}(j) &= 0; \\
\text{Fy}_{\text{est}}(j) &= 0; \\
\text{end} \\
\text{end} \\
\text{Fx}_{\text{ratio}} &= \text{Fx}_{\text{est}}; \\
\text{Fy}_{\text{ratio}} &= \text{Fy}_{\text{est}}; \\
\text{Fres}_{\text{ratio}} &= \sqrt{\text{Fx}_{\text{ratio}}^2 + \text{Fy}_{\text{ratio}}^2}; \\
\end{align*}
\]

\% Using the Kistler Force Profile Based Cutting Coefficients to simulate the Instantaneous Cutting Force

Ktc=676.4758; \% unit: N/mm^2 \\
Kte=21.4392; \% unit: N/mm \\
Krc=250.4006; \% unit: N/mm^2 \\
Kre=15.7230; \% unit: N/mm

\text{for \ j=1:numpercycle \ } \\
\quad \text{theta} = \text{(alpha+degree*(j-1))/180*pi}; \\
\quad \text{if} \ (\text{theta}>\text{enter}) \ \&\& \ ((\text{theta}-2\text{AD}\tan(\text{beta})/\text{D})<=\text{enter}) \\
\quad \quad \text{Fx}_{\text{est}}(j) = 0; \\
\quad \quad \text{Fy}_{\text{est}}(j) = 0; \\
\quad \quad \text{for \ k=1:L} \\
\quad \quad \quad \text{theta2} = \text{theta-2*tan(\text{beta})/D} \times \text{AD/L} \times k; \\
\quad \quad \quad \text{if} \ (\text{theta2}>\text{enter}) \\
\quad \quad \quad \quad \text{dFt} = (\text{Ktc}\times \text{ft} \times \sin(\text{theta2})+\text{Kte}) \times \text{AD/L}; \\
\quad \quad \quad \quad \text{dFr} = (\text{Krc}\times \text{ft} \times \sin(\text{theta2})+\text{Kre}) \times \text{AD/L}; \\
\quad \quad \quad \quad \text{dFx} = \text{-dFt} \times \cos(\text{theta2}) \times \text{-dFr} \times \sin(\text{theta2}); \\
\quad \quad \quad \quad \text{dFy} = \text{dFt} \times \sin(\text{theta2}) \times \text{-dFr} \times \cos(\text{theta2}); \\
\quad \quad \quad \quad \text{Fx}_{\text{est}}(j) = \text{Fx}_{\text{est}}(j) + \text{dFx}; \\
\quad \quad \quad \quad \text{Fy}_{\text{est}}(j) = \text{Fy}_{\text{est}}(j) + \text{dFy}; \\
\quad \quad \quad \text{else} \\
\quad \quad \quad \quad \text{break}; \\
\quad \quad \text{end} \\
\quad \text{end} \\
\quad \text{else} \text{ \{ otherwise \} } \\
\quad \quad \text{Fx}_{\text{est}}(j) = 0; \\
\quad \quad \text{Fy}_{\text{est}}(j) = 0; \\
\quad \quad \text{for \ k=1:L} \\
\quad \quad \quad \text{theta2} = \text{theta-2*tan(\text{beta})/D} \times \text{AD/L} \times k; \\
\quad \quad \quad \text{dFt} = (\text{Ktc}\times \text{ft} \times \sin(\text{theta2})+\text{Kte}) \times \text{AD/L}; \\
\quad \quad \quad \text{dFr} = (\text{Krc}\times \text{ft} \times \sin(\text{theta2})+\text{Kre}) \times \text{AD/L};
\[ dF_x = -dF_t \cos(\theta_2) - dF_r \sin(\theta_2); \]
\[ dF_y = dF_t \sin(\theta_2) - dF_r \cos(\theta_2); \]
\[ F_{x \text{ est}}(j) = F_{x \text{ est}}(j) + dF_x; \]
\[ F_{y \text{ est}}(j) = F_{y \text{ est}}(j) + dF_y; \]

```
end
elseif (\theta > \text{exit}) \&\& ((\theta - 2 \times AD \times \tan(\beta) / D) < \text{exit})
    F_{x \text{ est}}(j) = 0;
    F_{y \text{ est}}(j) = 0;
    for k = 1:L
        \theta_2 = \theta - 2 \times \tan(\beta) / D \times AD / L \times k;
        if (\theta_2 <= \text{exit})
            dF_t = (Ktc \times ft \times \sin(\theta_2) + Kte) \times AD / L;
            dF_r = (Kr \times ft \times \sin(\theta_2) + Kre) \times AD / L;
            dF_x = -dF_t \cos(\theta_2) - dF_r \sin(\theta_2);
            dF_y = dF_t \sin(\theta_2) - dF_r \cos(\theta_2);
            F_{x \text{ est}}(j) = F_{x \text{ est}}(j) + dF_x;
            F_{y \text{ est}}(j) = F_{y \text{ est}}(j) + dF_y;
        end
    end
else
    \theta_1 = \theta_2;
end
```

```
Fx_{\text{kistler \_ins}} = F_{x \text{ est}};
Fy_{\text{kistler \_ins}} = F_{y \text{ est}};
F_{\text{res \_kistler \_ins}} = \sqrt{F_{x_{\text{kistler \_ins}}}^2 + F_{y_{\text{kistler \_ins}}}^2};
```

```
%%
% Using the Smart Tool Force Profile Based Cutting Coefficients to simulate the Instantaneous Cutting Force
```

```
Ktc = 776.8609; \% unit: N/mm^2
Kte = 17.2415; \% unit: N/mm
Kr = 213.0565; \% unit: N/mm^2
Kre = 16.0614; \% unit: N/mm
```

```
for j = 1:numpercycle
    \theta = (\alpha + degree \times (j - 1)) / 180 \times \pi;
    if (\theta > \text{enter}) \&\& ((\theta - 2 \times AD \times \tan(\beta) / D) <= \text{enter})
        F_{x \text{ est}}(j) = 0;
        F_{y \text{ est}}(j) = 0;
        for k = 1:L
            \theta_2 = \theta - 2 \times \tan(\beta) / D \times AD / L \times k;
            if (\theta_2 <= \text{enter})
                dF_t = (Ktc \times ft \times \sin(\theta_2) + Kte) \times AD / L;
                dF_r = (Kr \times ft \times \sin(\theta_2) + Kre) \times AD / L;
                dF_x = -dF_t \cos(\theta_2) - dF_r \sin(\theta_2);
                dF_y = dF_t \sin(\theta_2) - dF_r \cos(\theta_2);
                F_{x \text{ est}}(j) = F_{x \text{ est}}(j) + dF_x;
            end
        end
    end
end
```
Fx_est(j) = Fy_est(j) + dFy;
else
    break;
end
end
elseif (theta<=exit) && ((theta-2*AD*tan(beta)/D)>=enter)
    Fx_est(j) = 0;
    Fy_est(j) = 0;
    for k=1:L
        theta2 = theta-2*tan(beta)/D*AD/L*k;
        dFt = (Ktc*ft*sin(theta2)+Kte)*AD/L;
        dFr = (Krc*ft*sin(theta2)+Kre)*AD/L;
        dFx = -dFt*cos(theta2)-dFr*sin(theta2);
        dFy = dFt*sin(theta2)-dFr*cos(theta2);
        Fx_est(j) = Fx_est(j) + dFx;
        Fy_est(j) = Fy_est(j) + dFy;
    end
elseif (theta>exit) && ((theta-2*AD*tan(beta)/D)<exit)
    Fx_est(j) = 0;
    Fy_est(j) = 0;
    for k=1:L
        theta2 = theta-2*tan(beta)/D*AD/L*k;
        if (theta2<=exit)
            dFt = (Ktc*ft*sin(theta2)+Kte)*AD/L;
            dFr = (Krc*ft*sin(theta2)+Kre)*AD/L;
            dFx = -dFt*cos(theta2)-dFr*sin(theta2);
            dFy = dFt*sin(theta2)-dFr*cos(theta2);
            Fx_est(j) = Fx_est(j) + dFx;
            Fy_est(j) = Fy_est(j) + dFy;
        else
            theta1 = theta2;
        end
    end
else
    Fx_est(j) = 0;
    Fy_est(j) = 0;
end
end

Fx_ST_ins = Fx_est;
Fy_ST_ins = Fy_est;
Fres_ST_ins = sqrt(Fx_ST_ins.^2 + Fy_ST_ins.^2);

figure;
plot(time_one,Fres,time_one,Fres_kistler_avg,time_one,Fres_ST_avg,time_one,Fres_ratio1,time_one,Fres_kistler_ins,time_one,Fres_ST_ins,'LineWidth',2);
xlabel('Time (s)');
ylabel('Resultant Force (N)');
legend('Measured','Simulated 1','Simulated 2','Simulated 3','Simulated 4','Simulated 5');
RE_kistler_avg = \frac{\text{abs}(\text{max}(F_{\text{res}}) - \text{max}(F_{\text{res}_\text{kistler avg}}))}{\text{max}(F_{\text{res}})}

RE_ST_avg = \frac{\text{abs}(\text{max}(F_{\text{res}}) - \text{max}(F_{\text{res}_{\text{ST avg}}}))}{\text{max}(F_{\text{res}})}

RE_ratio1 = \frac{\text{abs}(\text{max}(F_{\text{res}}) - \text{max}(F_{\text{res}_{\text{ratio1}}}))}{\text{max}(F_{\text{res}})}

RE_kistler_ins = \frac{\text{abs}(\text{max}(F_{\text{res}}) - \text{max}(F_{\text{res}_\text{kistler ins}}))}{\text{max}(F_{\text{res}})}

RE_ST_ins = \frac{\text{abs}(\text{max}(F_{\text{res}}) - \text{max}(F_{\text{res}_{\text{ST ins}}}))}{\text{max}(F_{\text{res}})}