UNIVERSITI TEKNIKAL MALAYSIA MELAKA

CUTTING FORCE COMPENSATION ANALYSIS USING PID CONTROL

This report submitted in accordance with requirement of the Universiti Teknikal Malaysia Melaka (UTeM) for the Bachelor Degree of Manufacturing Engineering (Robotic & Automation) with Honours

by

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DECLARATION

I hereby, declared this report entitled "Cutting force Compensation Analysis Using PID Control" is the results of my own research except as cited in references.

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APPROVAL

This report is submitted to the Faculty of Manufacturing Engineering of UTeM as a partial fulfilment of the requirements for the degree of Bachelor of Manufacturing Engineering (Robotics & Automation) with Honours. The member of the supervisory committee is as follow:

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ABSTRAK

Laporan ini dihasilkan berdasarkan judul "Kawalan daya pemotongan analisis dengan menggunakan kontroler PID". Dari judulnya, terdapat tiga unsur utama dalam projek ini, iaitu: kawalan daya pemotongan, analisis, dan kontroler PID. Secara keseluruhan, projek ini terdiri dari dua tahap, eksperimen analisis dan kontroler analisis. Fasa eksperimen akan menjalankan pengisaran proses dengan parameter yang dirancang, dan kemudian menangkap data gaya pemotongan semasa proses tersebut. Keputusan yang diambil akan dianalisis dengan menggunakan MATLAB. Pada tahap kedua, hasil dahulu digunakan sebagai isyarat gangguan dalam sistem kawalan. Berdasarkan pada pekerjaan sebelumnya, sistem urutan kedua fungsi dengan masa tunda yang digunakan untuk memcipta kontroler PID. PID direka menggunakan petanda plot. Beberapa kajian dilakukan pada kontroler PID, iaitu: kontroler tuning PID, PID kontroler pelacakan prestasi, dan pelacakan prestasi antara kontroler PID dan SMC sigmoid. PID kontroler digunakan dalam system dan ia dapat mengurangkan kesalahan kedudukan meja mesin. Prestasi sigmoid kawalan nonlinear SMC lebih baik dari kawalan PID linear. Projek ini dilakukan sampai simulasi dan akan dilanjutkan pada merangkumi kontroler PID menjadi real-time eksperimen.

ABSTRACT

The report is produced based on the title "Cutting force compensation analysis using PID controller". From the title, there are three main elements in this project, namely: cutting force compensation, analysis, and PID controller. In overall, the project consists of two phases, experiment analysis and compensation analysis. The experiment phase will conduct end milling with designed parameters, and then capture the cutting force signal during the process. The captured result will be analyzed by using MATLAB. In the second phase, the previous result is used as disturbance signal in the control system. Based on previous work, the second order system transfer function with time delay is used to design the PID controller. PID controller is designed using bode plot. A few studies are done on the design PID controller, namely: PID controller tuning, PID controller tracking performance, and tracking performance between PID controller and SMC sigmoid. The PID compensation is able to reduce the machine table position error. The performance of nonlinear controller SMC sigmoid is better than a linear PID controller. The project is done until simulation and it will be continued on covering the PID controller into real-time compensation.

DEDICATION

To My Parents

ACKNOWLEDGEMENTS

First of all, I would like to take the opportunity to my parents and say thank you. Their encouragement has given me a big motivation in continued my study in Malacca. I am here in Malacca UTeM is finally attained the chance to conduct this project with the knowledge given by UTeM. A second thanks is given to the lecturers in UTeM. Because of them, UTeM student capable to obtained ton of knowledge and benefit to their future.

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There are another two persons that I would like to appreciate a lot. Dr. Nizam who is provides the idea to operating the Kistler dynamometer and conducted a demonstration session during FYP 1. The second person Mr. Hafiz, a technician who is assists me to handle the experiment of performing end milling. A special thanks to them, Dr. Nizam and Mr. Hafiz.

Thousand thanks to Mr. Chiew tsung heng and Mr. Chey long sheng who many help on my project. They are willing to share their knowledge and partially contribute to my work. Thank you to them again.

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LIST OF ABBREVIATIONS & SYMBOLS

Abbreviations

D	-	Derivative
DAQ	-	Data Acquisition
FFT	-	Fast Fourier Transform
FYP	-	Final Year Project
GMS	-	Groundwater Modeling System
HSS	-	High Speed Steel
I	-	Integral
KF	-	Kalman Filter
LMA	-	Linear Mahnetic Actuator
MIMO	-	Multiple-Input and Multiple-output
P	-	Proportional
PD	-	Proportional-Derivative
PI	-	Proportional-Integral
PID	-	Proportional-Integral-Derivative
Q	-	Low Pass Filter
RC	-	Repetitive Controller
SMC	-	Sliding Mode control

Symbols

F	-	Force	[N]
R	-	Resultant Force	[N]
V	-	Cutting Speed	[mm/min]
D	-	Diameter	[mm]
N	-	Spindle Speed	[rev/min]
t_c	-	Undeformed Chip Thickness	[mm]

f	-	Feed-per-Tooth	[mm/tooth]
n	-	Number of Tooth	[Tooth]
d	-	Depth-of-Cut	[mm]
v	-	Feed Rate	[mm/min]
t	-	Cutting Time	[Sec]
l	-	Length of Cut	[mm]
w	-	Width of Cut	[mm]
MRR	-	Material Removal Rate	[mm^3/min]
γ	-	Rake Angle	[degree]
ϕ	-	Shear Plane angle	[degree]
τ	-	Friction Angle	[degree]
N	-	Force	[N]
K	-	Gain	
$G(s)$	-	Plant Transfer Function	
$G_c(s)$	-	Compensator Transfer Function	
$R(s)$	-	Input	
$C(s)$	-	Output	
L(z)	-	Discrete Time filter	
Q(z)	-	Discrete Time filter	
z^{-N}	-	Time Delay	
t	-	Time	[Sec]
f	-	Frequency	[Hz]
Y_R	-	Input Position	
Y	-	Output Position	
d	-	disturbance	
C(s)	-	Compensator	

CHAPTER 1
INTRODUCTION

1.1 Background

Milling is the most common form of machining which can create a variety of features on a part by cutting away the unwanted material. The flexibility feature of milling enables high precise cutting at high speed. The milling technology is getting advanced as the machine cutting speed increased and continues skyrocket. The high speed cutting is successfully shorten machining time, thus the production rate can be greatly improved. At the same time, the machine precision and accuracy have to be improved equivalently with high production speed.

The product quality may drop during a mass production when compares to job shop. This is due to the defects rate is inverse proportional to production rate. In order to improve the products quality, precision and accuracy is highly essential in development of machine technology. In the basics of milling, the disturbances that will affect precision are namely, cutting force and friction. The workpiece on the milling machine is unable to withstand the disturbances and causes tracking error or chattering on cutting tool.

The stated problem can be eliminates by implement control system in to the milling machine. A proper designed compensator is use to compensate the disturbances occur in milling machine. The disturbance affects the cutting result where the "spikes" is produce at the cutting edge. The disturbances can be identified by using sensor during performing milling. The sensor will capture the information of milling parameters such as spindle speed, depth-of-cut, and feed rate. Therefore, this project is going to design a controller to compensate the disturbance during end milling.

1.2 Problem Statement

The positioning error plays an important role in high precision milling process. The error may occur due to the stiffness of machine table. This project is focus on cutting force compensation. In order to design a compensator, the cutting force should be determined. The cutting force can be identified by performing end milling by using different parameters. The machining parameters should be determined during literature review.

1.3 Objective

(a) To identify the cutting force characteristic by using various milling parameters.

(b) To compensate the cutting force in the end milling by using PID controller.

1.4 Scope

This project focuses on,

(a) End milling by using a conventional milling machine.

(b) Milling parameters, namely: spindle speed, depth-of-cut, and feed rate.

(c) Linear cutting on x-axis. Circular cutting is not covered in this project.

(d) Table of milling machine in term of position accuracy.

(e) Cutting force compensation by using PID controller.

(f) Simulation by using MATLAB. Application of PID controller into actual cutting is not covered.

1.5 Organization

This project consists of six chapters. As the FYP 1, three first chapters have to complete. The chapter one introduces the project outline based on title given. The problem statement, objective, and scope are discussed in the first chapter. Chapter two is literature review. A deep research session is held in this chapter to study the theory in term of end milling parameters, disturbance, cutting force measuring method, and types of compensators. The methodology is discussed in next chapter. In chapter three, the procedure of handling experiment is discussed as well as the step of compensator designs.

The FYP 2 covers the last three chapters. The chapter four illustrates the result of experiment with PID controller. The result of cutting force compensation is analyze and discussed in this chapter. Chapter five is discussion session where the result of PID controller is further analyzed by comparing the system in two criteria, namely: disturbed system and compensated system. The MATLAB Simulink is used to analyze the PID controller systems. Last chapter, chapter six is project conclusion section.

CHAPTER 2

LITERATURE REVIEW

In this chapter, mainly consists of three topics, the milling process, cutting force measurement and cutting force compensation. The milling process will be introduced as the basic process and the types. There are two general disturbance in milling process and it being discussed. The disturbances are friction force and cutting force during milling process. In this research, we are only concern the cutting force. The parameter that is affecting the milling operation is discussed. In order to investigate the cutting force, number of literature research is essential to be done. Cutting force measuring method is used to capture the result by using external resources. As general, there are two measuring class which is directly and indirectly. Directly measuring is a method to obtain the cutting force through contacting forces and sensor such as dynamometer. Indirectly measuring usually refer to those obtain the cutting force without contacting such as motor current measurement. General compensation model is discussed and compared.

2.1 Milling Process

Milling is a machining operation in which a workpiece is fed past a rotating cylindrical tool with multiple cutting edges (Kalpakjian and Schmid, 2006). The axis of rotation of the tool is perpendicular to the feed direction. Mostly plane surfaces are created through milling. Milling process is typically used to produce parts that are not axially symmetric and have many features, such as holes, slots, pockets, and even three dimensional surface contours. In milling process, the speed and motion of the cutting tool is specified through several parameters. These parameters are selected for each operation based upon the workpiece material, tool material, tool size, and more.

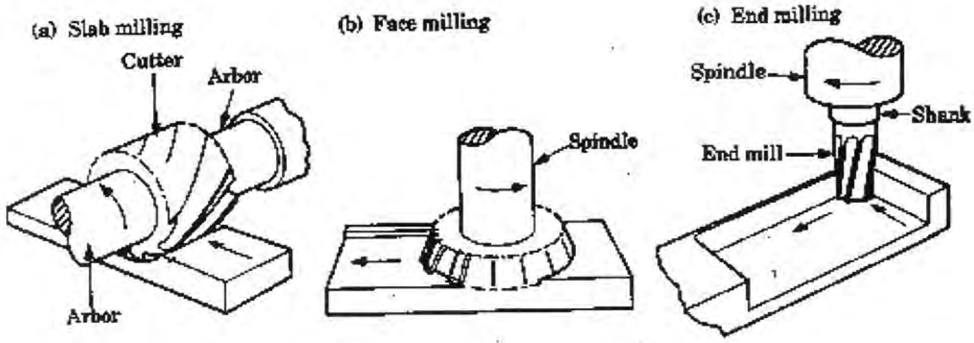

Figure 2.1: Milling operation (Kalpakjian and Schmid, 2006)

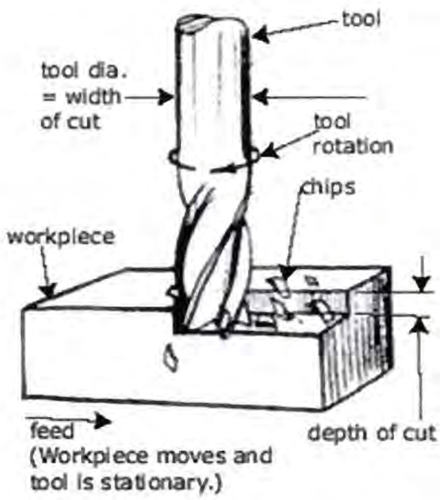

Figure 2.2: Milling parameters (retrieved from www.oshore.com)

There are number of milling process such as face milling, end milling and peripheral milling. However, the end milling is the only focus in this research. End milling is an improvement version of drilling. The end milling allows all direction cutting instead of axial direction cutting of drilling and usually can be found at vertical machine. End milling can perform operations such as pocketing and slotting. The cutter in end milling is call end mill. There are several shapes of end mills to perform different task: a normal which is tilted to machine-tapered surfaces, hemispherical ends (ball nose) and hollow end mill. End mills are made of high-speed steels or have carbide inserts.

2.2 Disturbance on Milling Operation

Disturbances affect almost every type of control system. In a furnace, heat disturbances from the atmosphere or neighboring furnaces make temperature more difficult to control. Load currents can act like a disturbance to a power supply, pulling the output voltage away from the target. In each case, an undesired source of power is added to the power converter output and fed to the plant. In result, the plant state is disturbed.

According to Jamaludin (2008), there are two primarily disturbance forces that can critically affect tracking performance and workpiece finishing quality in a linear motion based milling cutting process are friction and cutting forces. The effect of disturbance causes the "spikes" on the workpiece cutting path. The "spikes" is widely known as quadrant glitch (figure 2.3).

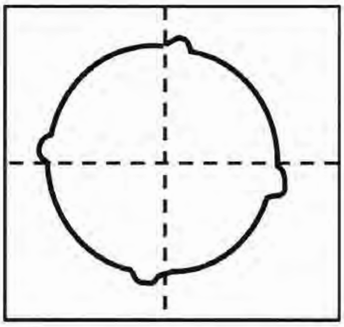

Figure 2.3: Quadrant Glitches (Jamaludin, 2008)

Quadrant glitches in circular motion are the product of complex nonlinear behavior of friction during the motor reversal motion or near zero velocity on each axis of a motion system. The friction force is an undesired nonlinear phenomenon that generates from the motor and the support bearings. Friction is categorized according to its pre-sliding and sliding regimes. In pre-sliding regime, friction force is principally dependent on displacement (figure 2.4). On the other hand, the friction force of sliding regime is predominantly dependent on the sliding velocity.

The cutting force act as an input disturbance on the motion control system during cutting processes. The cutting force actually produces noise toward the workpiece and cutter as well during the operation. The noises usually appear as vibration and stiffness problem. The vibration normally occurs at two spots, cutter and workpiece. However, to decrease the vibration, the cutter or workpiece have to be stiff to withstand the cutting force. Therefore, cutting force compensation is essential to minimize distortion of machine component, maintain the desired dimensional accuracy of machined part. The further detail of cutting force will be discussed in next section.

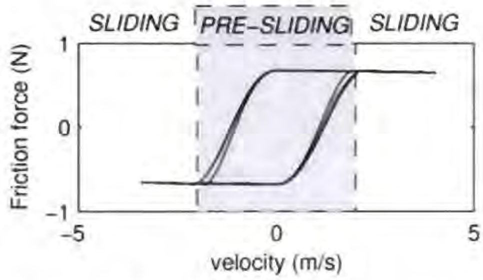

Figure 2.4: Pre-sliding and sliding friction regimes (Jamaludin, 2008)

Generally, the cutting force or friction force will affect disturbance to milling process such as tracking error, quadrant glitch, and stiffness lose. The mentioned disturbed effects are in relation. The tracking error and quadrant glitch is cause by stiffness of the milling work table. The milling work table had to compensate in order to overcome the stated problem. To design a compensator, the cutting force identification will come to first. The friction force is neglect in this research. The cutting force measuring method will discuss in section 2.4.

2.3 Cutting Force on Milling Operation

According to Kalpakjian and Schmid (2006), there are three main forces during cutting process, which is cutting force (F_c), thrust force (F_t) and resultant force (R). The cutting force acts in the direction of the cutting speed, V, and supplies the energy required for cutting. The ratio of the cutting force to the cross-sectional area (width of cut or depth-of-cut) being cut is referred to as the specific cutting force. The thrust force acts in a direction normal to the cutting speed. The resultant force is a force combination of cutting force and thrust force. A graphical previews of the forces that acting in cutting zone in figure 2.5.

From the statement above, the cutting speed and depth-of-cut is the crucial parameter which straightly affecting the cutting force. The formulas which related to the milling parameter are discussed. The cutting speed, V in milling operation is the surface speed of the cutter, or

$$V = \pi D N \tag{2.1}$$

where D is the cutter diameter and N is the spindle speed. For the straight tooth cutter, the approximate undeformed chip thickness, t_c is derive as equation

$$t_c = 2f\sqrt{\frac{d}{D}} \tag{2.2}$$

where f is the feed-per-tooth of the cutter and d is the depth-of-cut. The feed rate, v is then determined from the equation

$$v = fNn \tag{2.3}$$

where the n is the number of teeth on the cutter. The cutting time, t is given by expression

$$t = \frac{l + lc}{v} \tag{2.4}$$

where l is length of cut and lc is the extent of the cutter's first contact with workpiece. From the equations above, the material removal rate (MRR) is form as

$$MRR = \frac{lwd}{t} = wdv \tag{2.5}$$

The w is usually referring to width of cut. Based on the equations, the parameters are all relevant to each other.

From the equation 2.1, the cutting speed is always proportional to the spindle speed with condition cutting diameter is fix. Equation 2.3 shows the feed rate is proportional to the feed per tooth or spindle speed. When adjusting feed rate, the feed per tooth is seldom vary in a system due to the difficulty of accuracy controlling. Therefore, the spindle speed is the common variable for feed rate. The relation of feed per tooth and depth-of-cut is inverse proportional by understanding equation 2.2. The cutting time is depends on the feed rate when the experiment is repetitive (equation 2.4). From equation 2.5, depth-of-cut and feed rate is the main element in MRR. In summary, the spindle speed is inversely proportional to feed rate; the depth-