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JUDUL: **EXPERIMENTAL VALIDATION FOR CHATTER STABILITY PREDICTION**

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EXPERIMENTAL VALIDATION FOR
CHATTER STABILITY PREDICTION

MUHAMMAD AZWAN BIN ZAINOL ABIDIN

Report submitted in partial fulfillment of the requirements
for the award of Bachelor of Mechanical Engineering.

Faculty of Mechanical Engineering
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JUNE 2012

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FACULTY OF MECHANICAL ENGINEERING

I certify that the project entitled *"Experimental Validation for Chatter Stability Prediction"* is written by *Muhammad Azwan Bin Zainol Abidin*. I have examined the final copy of this project and in my opinion; it is fully adequate in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering. I herewith recommend that it be accepted in partial fulfillment of the requirements for the degree of Bachelor of Mechanical Engineering.

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I hereby declare that the work in this report is my own except for quotations and summaries which have been duly acknowledged. The report has not been accepted for any degree and is not concurently submitted for award of other degree.

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Special thanks to my parents for their support and cares, also for my siblings.
Special dedications for my supervisor on his guiding towards my project.

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ABSTRACT

This research focused on the experimental validation for chatter stability prediction. An optimum machining was aimed to maximize the material removal rate, whilst maintaining a sufficient stability margin to assure the surface quality. High material removal rate in machining produced self-excited vibration or chatter of the cutting tool and the workpiece. This resulted in a poor surface finish and dimensional accuracy, chipping of the cutter teeth, and also may damage the workpiece as well as machining tool. Frequency response function of a single degree freedom flexural was measured and the cutting stiffness of tools were determined in order to be used in predicting chatter stability using semi discretization method. The aluminium 7075 specimens were used in the milling cutting experiment to validate the chatter stability diagram of mill uniform and variable cutters, where a set of spindle speed and depth of cut had tested. The vibration conditions of machining were identified by analysing the vibration signals and FFT spectrum whether it was stable or in a chatter condition. There are good agreement between predicted stability and cutting experiment for the down-milling operation using uniform 4 flute cutting tool. Stable conditions were shown outside the boundary of chatter region. The optimized cutting tool was predicted to suppress chatter. Machining experiment tests showed there were no chatter vibration conditions during machining process until 1.5 mm depth of cut. According to the results of machining experiment, it was proven that the variable tool had more capability to machining without producing chatter vibration as compared to the regular tool.

ABSTRAK

Penyelidikan ini adalah berkenaan eksperimen pengesahan untuk ramalan kestabilan keterujaan getaran. Sasaran pengoptimuman pemesinan adalah untuk memaksimumkan kadar penyingkiran bahan, pada masa yang sama mengekalkan margin kestabilan untuk memastikan kualiti permukaan. Kadar penyingkiran bahan yang tinggi dalam pemesinan menghasilkan keterujaan getaran oleh alat pemotong dan bahan kerja. Hal ini seterusnya menyebabkan kemasan permukaan dan ketepatan dimensi yang rendah, mengumpil gigi alat memotong, dan boleh merosakkan bahan kerja serta alat pemesinan. Fungsi respon frekuensi bagi struktur fleksibel satu darjah kebebasan telah diukur dan kekukuhan pemotongan bagi alatan pemotong telah ditentukan untuk diaplikasikan dalam meramal kestabilan keterujaan getaran menggunakan kaedah pendiskretan separuh. Spesimen aluminium 7075 digunakan dalam eksperimen pemotongan *milling* untuk mengesahkan rajah kestabilan keterujaan getaran bagi alat pemotong seragam dan berubah-ubah, di mana suatu set kelajuan pengumpar dan kedalaman pemotongan telah diuji. Keadaan getaran pemesinan telah dikenalpasti dengan menganalisis isyarat getaran dan spectrum FFT, sama ada dalam keadaan stabil atau pun keterujaan getaran. Terdapat persetujuan yang memuaskan antara kestabilan yang diramalkan dengan eksperimen pemotongan bagi operasi *down-milling* menggunakan alat memotong 4 ulir seragam. Keadaan stabil ditunjukkan pada luar sempadan kawasan keterujaan getaran. Alat pemotong optimum telah diramalkan dapat menghapuskan keseluruhan keterujaan getaran. Ujian-ujian eksperimen pemotongan menunjukkan bahawa tiada keterujaan getaran berlaku semasa pemesinan sehingga kedalaman pemotongan 1.5 mm. Merujuk kepada hasil eksperimen pemotongan, terbukti bahawa alatan pelbagai adalah lebih berkeupayaan untuk pemesinan tanpa berlakunya keterujaan getaran, berbanding dengan alatan biasa.

TABLE OF CONTENTS

		Page
SUPERVISOR'S DECLARATION		iv
STUDENT'S DECLARATION		v
ACKNOWLEDGEMENTS		vii
ABSTRACT		viii
ABSTRAK		ix
TABLE OF CONTENTS		x
LIST OF TABLE		xiii
LIST OF FIGURES		xiv
LIST OF ABBREVIATIONS		xvi
CHAPTER 1	**INTRODUCTION**	1
1.1	Project Background	1
1.2	Objectives of The Research	2
1.3	Scope of The Research	2
1.4	Flow Chart	2
CHAPTER 2	**LITERATURE REVIEW**	4
2.1	Introduction	4
2.2	Machining	5
2.3	Chatter in Machining	7
	2.3.1 Chatter Phenomenon in Milling	8
	2.3.2 Progression in Chatter Research	8
	2.3.3 Chatter Stability Experiment	10
2.4	Milling Machining	11
	2.4.1 Types of Milling Operations	12
	2.4.2 Methods of Metal Cutting	13
	2.4.3 Speed, Feed and Depth of Cut	14
2.5	Fast Fourier Transform (FFT)	17

2.6 Summary 18

CHAPTER 3 METHODOLOGY 19

3.1 Introduction 19
3.2 Experiment Procedure 19
3.2.1 Build a Flexure 21
3.2.2 Frequency Response Function (FRF) 21
3.2.3 Cutting Stiffness Determination 23
3.2.4 Milling Cutting Tool 24
3.2.5 Chatter Stability Prediction 25
3.2.6 Prepare of Material (Workpiece) 25
3.2.7 Machining Experiment 26
3.3 Result Analysis 29

CHAPTER 4 RESULTS AND ANALYSIS 30

4.1 Introduction 30
4.2 Chatter Stability Identification 30
4.3 Chatter Stability Comparison 37
4.4 Summary 40

CHAPTER 5 CONCLUSION AND RECOMMENDATIONS 41

5.1 Conclusion 41
5.2 Recommendations 42

REFERENCES 43

APPENDICES 45
A Gantt Chart 45
B Frequency Response Function of Flexure 47
C Matlab Code for Chatter Stability Prediction 48
D Chatter Stability Lobes Diagram 50
E Haas VF6 Milling Machine Specifications 51

F	CNC Code for Milling Process	52
G	Piezoelectric Accelerometer (PCB 352C03) Specifications	53

LIST OF TABLE

Table No.		Page
2.1	Recommended cutting speed and feed for milling	15

LIST OF FIGURES

Figure No.		Page
1.1	Project flow chart	3
2.1	A forged crankshaft before and after machining the bearing surface	6
2.2	The complex parts of product produced using machining	6
2.3	Poor surface finish of product caused by chatter of machining	7
2.4	Chipping of the cutter teeth on the tool	8
2.5	Dynamic model of milling with two degrees of freedom	9
2.6	Cutting experiment	11
2.7	Two basic types of milling operations: (a) peripheral milling and (b) face milling	12
2.8	Up milling operation: (a) direction of cutter rotation and (b) the chip cut by a cutter tooth	13
2.9	Down milling operation: (a) direction of cutter rotation and (b) the chip cut by a cutter tooth	14
2.10	Relationship between actual and nominal milling feed	17
3.1	Flow chart of methodology	20
3.2	Flexure of experiment	21
3.3	Bruel & Kjaer model type 7539A 5/1 channel	22
3.4	2302-10 Meggit Hammer	22
3.5	4507B Bruel & Kjaer accelerometer	22
3.6	Example of clamping the workpiece on dynamometer force	23
3.7	Tool geometry for experimental validation: (a) uniform helix, (b) variable helix, (c) uniform pitch and (d) variable pitch	24
3.8	Band Saw Machine	25

3.9	Aluminium 7075 specimen	26
3.10	Haas VF6 Milling Machine	27
3.11	Piezoelectric accelerometer (PCB 352C03)	27
3.12	National Instrument High Speed USB Carrier NI USB-9162	28
3.13	Cutting experiment setup: (a) schematic diagram and (b) accelerometer location	28
4.1	Experiment result from point A (4750 rpm, 0.25 mm): (a) acceleration signal and (b) FFT spectrum	31
4.2	Experiment result from point C (3750 rpm, 1.0 mm): (a) acceleration signal and (b) FFT spectrum	32
4.3	Experiment result from point F (5000 rpm, 1.25 mm): (a) acceleration signal and (b) FFT spectrum	33
4.4	Experiment result from point B (4750 rpm, 0.75 mm): (a) acceleration signal and (b) FFT spectrum	34
4.5	Experiment result from point D (4750 rpm, 1.0 mm): (a) acceleration signal and (b) FFT spectrum	35
4.6	Experiment result from point E (5250 rpm, 1.25 mm): (a) acceleration signal and (b) FFT spectrum	38
4.7	Chatter stability prediction diagram for uniform cutting tool	37
4.8	Experimental validation results for uniform cutting tool	38
4.9	Chatter stability prediction diagram for variable cutting tool	39
4.10	Experimental validation results for variable cutting tool	40

LIST OF ABBREVIATIONS

CNC	Computer numerical control
CS	Cutting speed
DE	Differential Evolution
FFT	Fast fourier transform
FKM	Fakulti Kejuruteraan Mekanikal
FRF	Frequency response function
HSS	High-speed steel
RPM	Revolution per minute
USB	Universal serial bus

CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

In terms of annual dollars spent, machining is the most important of the manufacturing processes. Machining can be defined as the process of removing material from a workpiece in the form of chips. The term metal cutting is used when the material is metallic. Most machining has very low set-up cost compared to forming, molding, and casting processes. However, machining is much more expensive for high volumes. Machining is necessary where tight tolerances on dimensions and finishes are required.

Optimum machining aims to maximize the material removal rate, whilst maintaining a sufficient stability margin to assure the surface quality. High material removal rate in machining produces self excited vibration or chatter of the cutting tool and the workpiece. When the machining becomes unstable, the excessive vibrations of the cutter and workpiece result in poor surface finish and dimensional accuracy, chipping of the cutter teeth, and may damage the workpiece and machining tool.

In the early stage of the machining chatter research, the presence of negative damping was considered as the only source of chatter. Further research focused on the particular of parameter selections in machining to avoid the build-up of these undesired oscillation and on the analytical predictions of chatter.

In this research project, to predict chatter, analytical stability can be used to define stable and unstable condition for specific spindle speed and depth of cut. The machining can be optimized by determining the best combination of the chip loads and spindle speeds with the constraint of chatter instability.

1.2 OBJECTIVES OF THE RESEARCH

The followings are the objectives of the project:

i. Prepare specimens of material Aluminum 7075.
ii. Validate chatter stability prediction with cutting experiment.
iii. Compare chatter stability of regular and variable milling tool.

1.3 SCOPE OF THE RESEARCH

Scopes for this project is built a single degree of freedom flexural as the first required to be used in the experiment. For the next step, experiment will go through modal testing, (commonly the impact hammer testing) and cutting stiffness determination. The natural (modal) frequencies, modal masses, modal damping ratios and mode shapes of the object under test are determined by modal testing. This information will use to predict chatter stability using semi discretization method.

Then, validate regular tool cutting chatter stability with cutting experiment using CNC milling machine. Experiment is conducted to compare chatter analytical prediction. Cutting experiments will use the variable helix and variable pitch tool to validate chatter milling tool chatter stability.

1.4 FLOW CHART

The sequence of work has been planned as shown in Figure 1.1 in order to achieve the objectives of this research, while Gantt Charts can refer to Appendix A. This flow chart is useful as guideline to ensure that the experiment is carried out smoothly. The process involved in achieving notified objectives are including literature study based on related topic, determining material, method and parameters, conducting experiment, analysis data and data discussion.

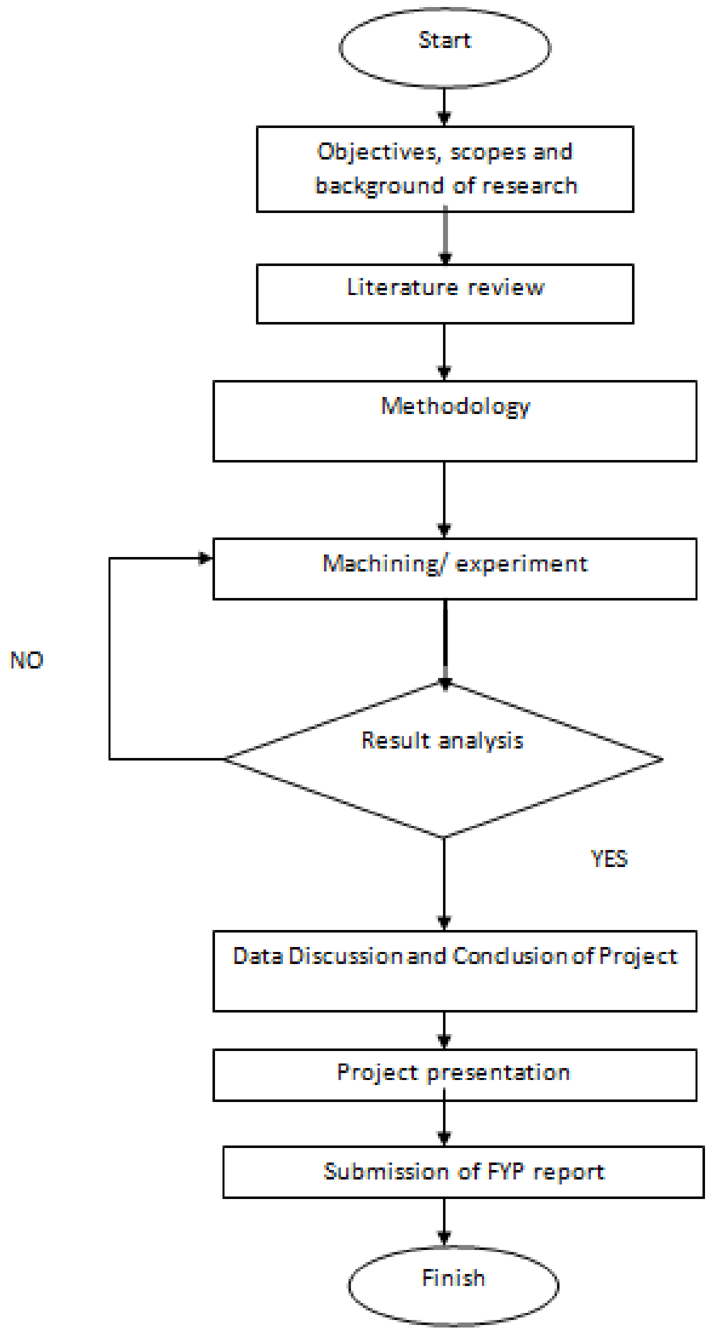


Figure 1.1: Project flow chart

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The science, engineering and technology of manufacturing process and systems continue to move on speedily on a worldwide scale and with major impact on the financial systems of all peoples. This is because with this condition people can invent many products with various shapes. As a result, that science, engineering and technology of manufacturing processes and system people can do many things.

With knowledge of manufacturing, till today many kinds of manufacturing have been generated. To produce parts, need variety of manufacturing processes. These can be broadly classified into five groups (Nagendra and Mittal, 2006). In the casting process, the material is given the desired shape and size of the product by melting it, poured into a cavity and allowing it to solidify. Machining is a removing the unwanted material from a given workpiece to give it the required shape.

Forming is made use of suitable force, pressure or stresses like compression, tension, shear or their combination to cause a permanent deformation of the material to give it the required shape. In powder metallurgy process, fine powdered materials are blended, pressed into a desired shape in an die and then heated in a controlled atmosphere to bond the contacting surfaces of the particles and get the desired properties. In joining process, two or more pieces are joined together permanent, semi-permanent or temporary.

2.2 MACHINING

The parts of products will require further manufacturing operations after it's done through the forming and shaping processes. The situation happens because none of these processes are capable of producing parts with such specific characteristics. Machining is described as a group of processes that consist of the removal of material and modification of the surface of the workpiece after it has been produced by various methods (Kalpakjian and Schmid, 2006).

In general, machining consist of several major types material-removal processes, such as cutting process, typically involving single-point or multipoint cutting tools, each with a clearly defined shape. Another that, abrasive processes, such as grinding and advanced machining processes, for example utilizing electrical, chemical, laser, thermal and hydrodynamic methods.

Machining without qualification usually implies conventional machining and the removal of material. With the recent proliferation of additive manufacturing technologies, conventional machining has been retronymously classified, in thought and language, as a subtractive manufacturing method. In narrow contexts, additive and subtractive methods may compete with each other. In the broad context of entire industries, their relationship is complementary. Each method has its own advantages over the other. While additive manufacturing methods can produce very intricate prototype designs impossible to replicate by machining, strength and material selection maybe limited (Beaman *et al.*, 2004).

The extreme dimensional accuracy can be got by machining process, often more so than any other process alone. Machining can produce sharp corners and flatness on a part that may not be able to be created through other processes. Machining accuracy allows it to produce surface finish and smoothness that can't be achieved any other way, as shown in Figure 2.1. A very complex parts can be made by machining operation, as shown in Figure 2.2.

Figure 2.1: A forged crankshaft before and after machining the bearing surface

Source: Courtesy of Wyman-Gordon Company, 2011

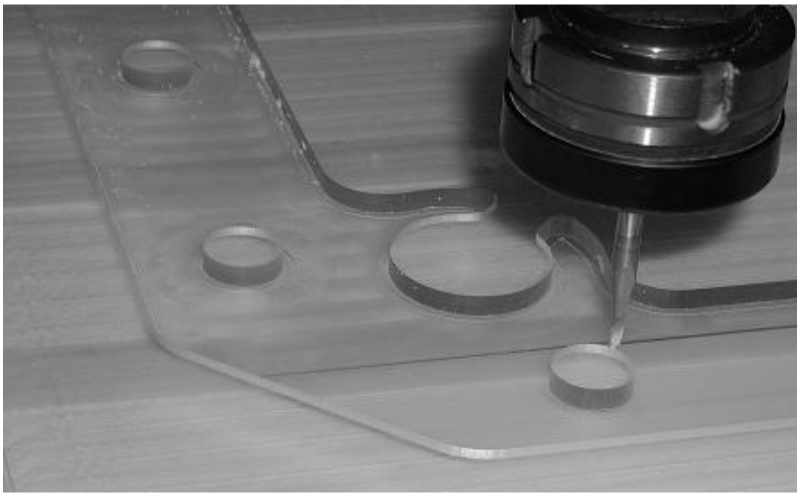


Figure 2.2: The complex parts of product produced using machining

Source: Protogenic Division, Spectrum Plastics Group, 2011

2.3 CHATTER IN MACHINING

The self-excited oscillations of the cutting tool and the workpiece can be referred as machine tool chatter vibrations. If the closed-loop machining system, which include machine tool-cutter dynamic cutting process, become unstable, the excessive vibrations of the cutter and workpiece result in a poor surface finish and dimensional accuracy, chipping of the cutter teeth, and may damage the workpiece and machine tool, as shows in Figures 2.3 and 2.4. Generally, conservative material removal rates, which cause reduced productivity, are used to avoid chatter vibrations (Budak and Altintas, 1998).

Optimum machining aims to maximize the material removal rate, while maintaining a sufficient stability margin to assure the surface quality with avoid the chatter. There are two groups of machine tool chatter, regenerative and non-regenerative (Tlusty, 1985). Regenerative chatter occurs due to the periodic tool passing over the undulations of the previously cut surface, while non-regenerative chatter has to do with mode coupling among the existing modal oscillations.

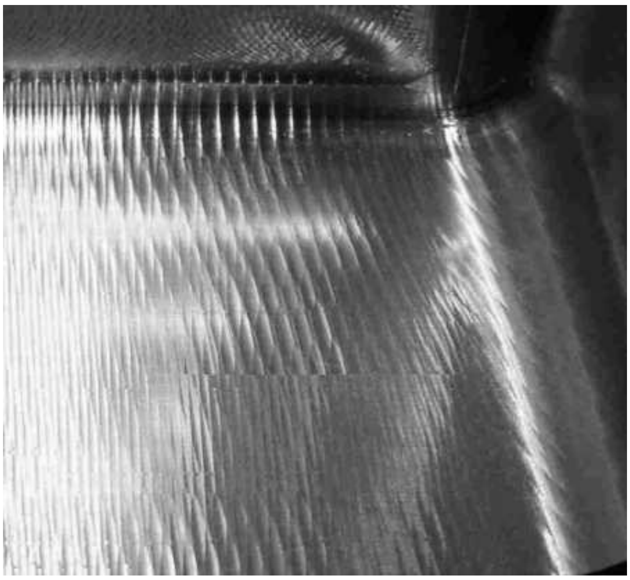


Figure 2.3: Poor surface finish of the product caused by the chatter of machining

Figure 2.4: Chipping of the cutter teeth on the tool

2.3.1 Chatter Phenomenon in Milling

During the milling process, one of the structural modes of the machine tool – workpiece system is excited by cutting force initially. Same as Figure 2.5, an oscillatory surface finish left by one of the tooth is removed by the succeeding oscillatory tooth due to structural vibrations. The resulting chip thickness becomes also oscillatory, this in turn produces oscillatory cutting forces whose magnitudes are proportional to the time varying chip load. This condition makes the self excited cutting system becomes unstable. Then, chatter vibrations grow until the tool jumps out of the cut or break under the excessive cutting forces (Altintas and Budak, 1995). That's why the major limiting factor in increasing the material removal rates of the machine tools is chatter vibration.

2.3.2 Progression in Chatter Research

The papers about chatter as a regenerative phenomenon were published (Tobias *et al.*, 1958). Later, research presented the problem as a feedback loop, which clarified a lot of formulation (Merritt, 1965). These basic approaches were used, by reducing the dynamics of the machine to an equivalent single degree of freedom system for many years.

Next, the method which enables working with several degree freedom models is presented (Altintas and Budak, 1995) as shown in Figure 2.5. Analysis for the geometrical nonlinearities of the milling process obtained an approach to the solution by using a Fourier series development of the directional factors and solved the system by considering the zero order term only. In next research, researcher worked out the system by considering several terms of the Fourier development, which gives rise to solutions very close to those obtained by using the fundamental term only (Budak and Altintas, 1998).

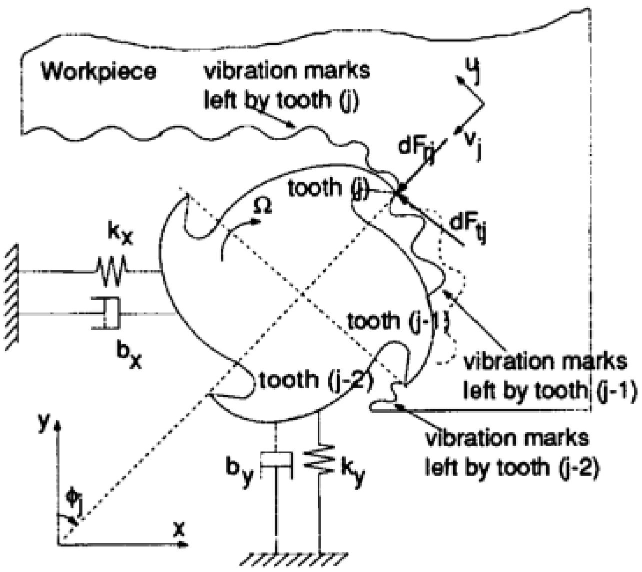


Figure 2.5: Dynamic model of milling with two degrees of freedom

Source: Altintas and Budak, 1995

Researchers have proposed analytical methods that explicitly account for the interrupted nature of milling and have generated stability diagrams analogous to the classical ‘lobes’. The intermittent was captured by including many harmonics in the Fourier series of the time-varying coefficients (Corpus and Endres, 2000). This approach loses accuracy as the relative time in the cut decreases.

The single frequency approach has been shown to be very precise, but when radial immersion of the mill is small, the existence of additional stability lobes was found. A discrete map model for highly interrupted milling processes was used (Davies *et al.*, 2000), where the time in the cut is infinitesimal and the cutting process is modeled as an impact. An approximate expression was derived for the time delay in the form of an integral, time-periodic matrix differential equation, and use Floquet theory to determine stability boundaries (Insperger and Stepen, 2000). Later, the technique of semi-descretization was developed (Insperger and Stepen, 2004), while the similar results using temporal finite elements was obtained (Bayly *et al.*, 2003).

The multifrequency resolution is also able to present accurately the flip instability phenomenon was showed (Merdol and Altintas, 2004). In specific research, just a few papers analyzed the chatter in milling with the inclusion of the effect of the helix angle. Without associated with the helix angle of the milling, some papers present some instability regions with ‘lenticular’ shape (Govekar *et al.*, 2005).

Most commonly chatter research has focused to increase the material removal rate while avoiding the onset of chatter. A natural progressive trend is to increase the productivity through simultaneous (or parallel) machining. This process can be further optimized by determining the best combination of the chip loads and spindle speeds with the constraint the chatter instability (Olgac and Sipahi, 2005).

2.3.3 Chatter Stability Experiment

Many researches were done to investigate the chatter vibration condition in machining. Generally, the milling process was used in cutting test to find out the chatter stability based on the parameters, spindle speed and depth of cut, as shown in Figure 2.6. Chatter that happen can produce an unpleasant sound and noise, lower machining quality, poor surface finish and accuracy. The cutter tools that commonly used have a higher probability to produce excessive vibration and chatter. Thus, the irregular cutting tool was designed using an optimization process like Differential Evolution (DE), to suppress unwanted chatter vibration during milling operations.

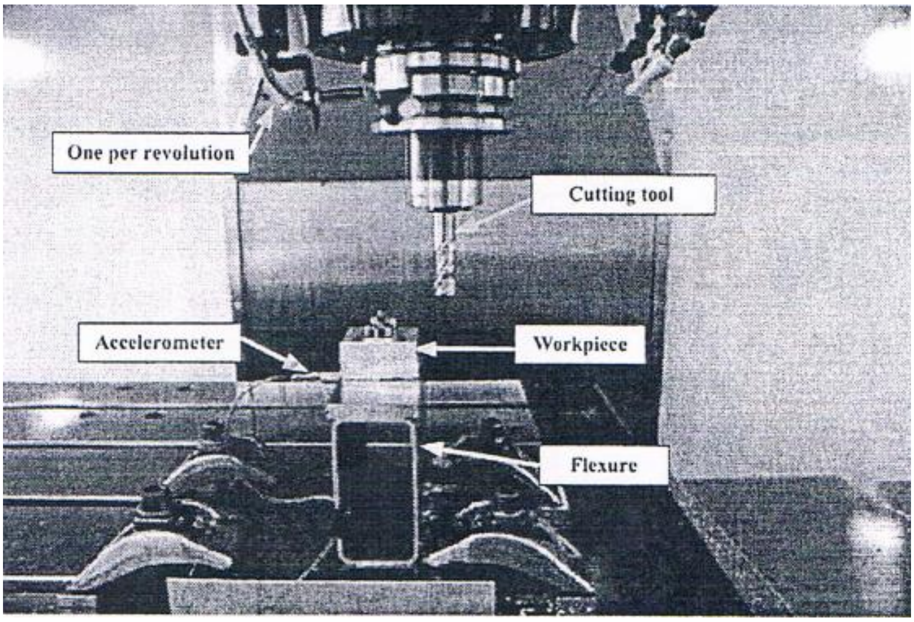


Figure 2.6: Cutting experiment

Source: Yusoff *et al.*, 2011

The identification of chatter can be done when analysis the result of cutting process, such as surface roughness test and analysis of vibration signal during machining. Some investigation has analyzed vibration condition based on the 1/Rev samples and spectrum analysis (Yusoff *et al.*, 2011). The result was classified as chatter if the vibration signal shows that 1/Rev samples approached a fixed point with a variance less 10 mm/s^2 and the FFT amplitude was dominated by the tooth passing harmonics.

2.4 MILLING MACHINING

Milling machine can machine flat or curved surfaces, inside or outside, of almost all shapes and sizes. Milling is a machining operation in which a work part is fed past a rotating cylindrical tool with multiple cutting edges (in rare cases, a tool with one cutting edge, called as fly-cutter is used). The direction of feed is perpendicular to the axis of rotation of the cutting tool. This orientation between the tool axis and the feed direction is one of the features that distinguish milling from drilling. Owing to the variety of shapes possible and its high production rates, milling is one of the most versatile and widely used machining operations.

2.4.1 Types of Milling Operations

There are two types of milling operations (Groover, 2007), shown in Figure 2.7. In peripheral milling (plain milling), the surface being machined is parallel to the axis of the tool, and the operation is performed by cutting edges on the outside periphery of the cutter. In face milling, the axis of the cutter is perpendicular to the surface being milled, and machining being performed by cutting edges on both the end and outside periphery of the cutter.

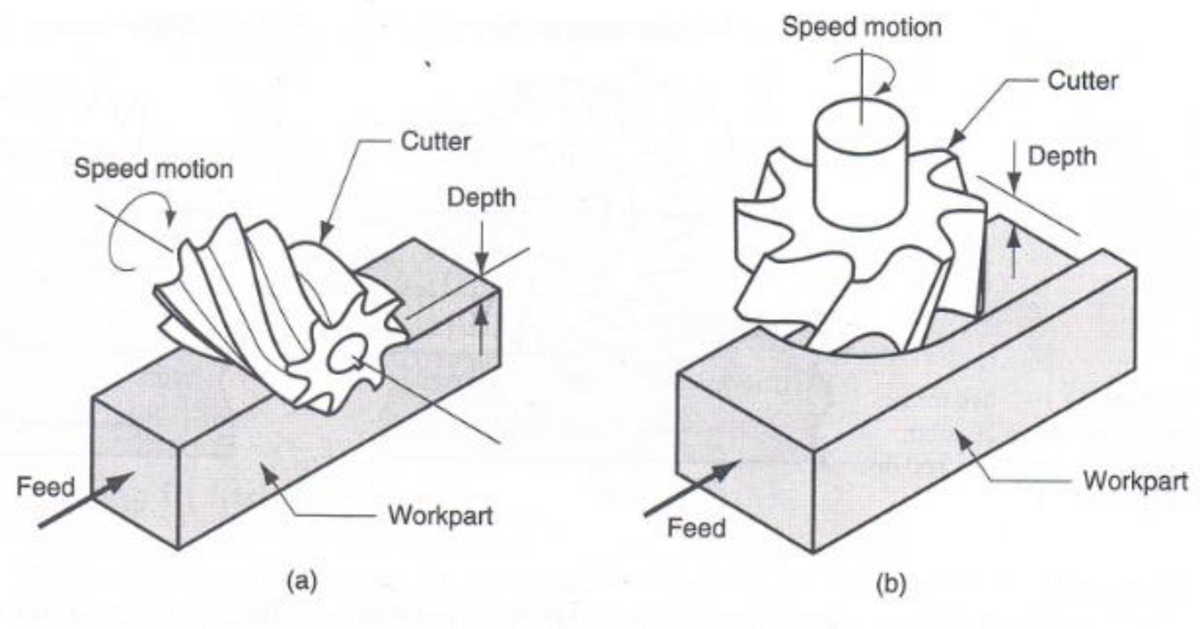


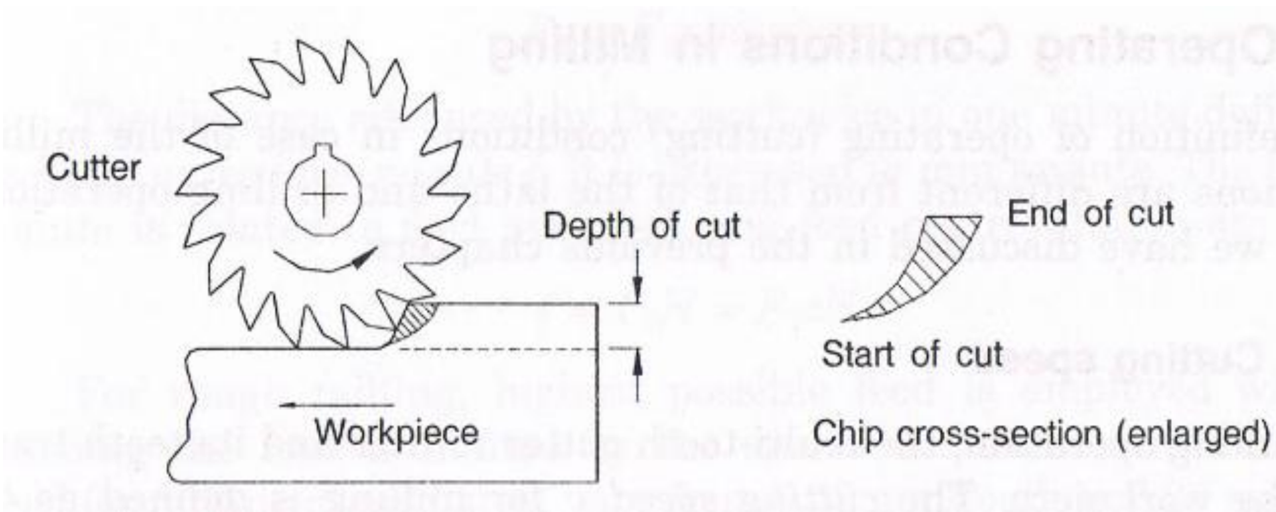
Figure 2.7: Two basic types of milling operations:
(a) peripheral milling and (b) face milling

Source: Groover, 2007

2.4.2 Methods of Metal Cutting

There are two methods of metal cutting in the milling operation, up milling and down milling. The difference of operations lies in the direction along which the workpiece is fed into the rotating milling cutter and the direction of rotation of the cutter (Nagendra and Mittal, 2006).

In up milling (conventional milling), the direction of the cutter rotation is opposite to the feed direction of the workpiece, as shown in Figure 2.8. Each tooth of the cutter starts the cut with zero depth of cut, reaches the maximum value as the tooth leaves the cut. The cutter has to be forced into the material, creating a burning effect with excessive friction and high temperature. The difficulty is experienced in pouring coolant on the cutting edge, make chips accumulate and may be carried over with the cutter, thus spoiling the surface finish (slightly wavy surface).

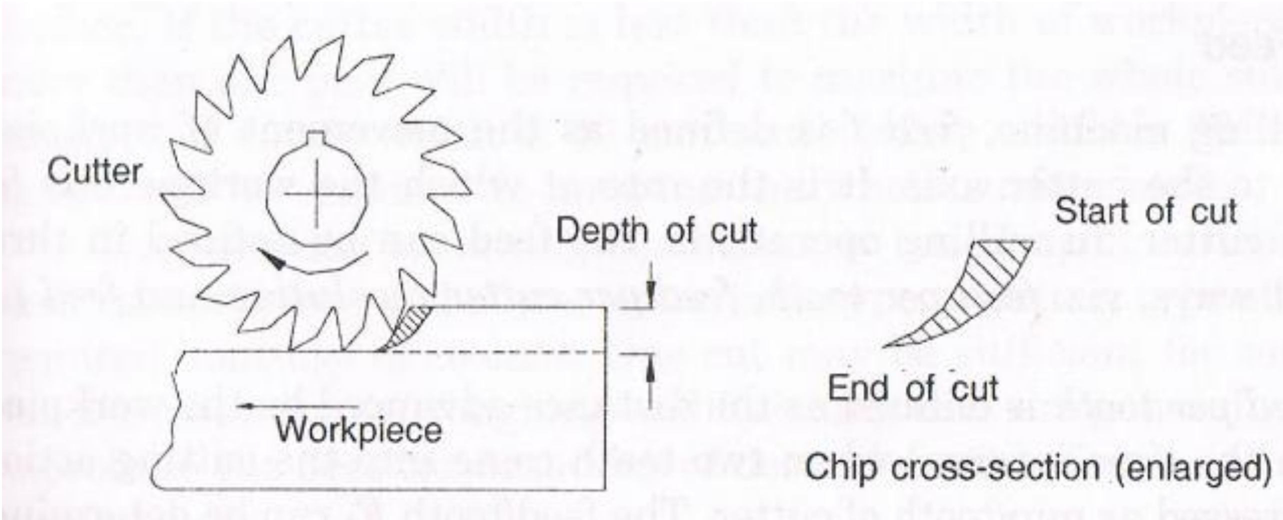


(a) (b)

Figure 2.8: Up milling operation: (a) direction of the cutter rotation and (b) the chip cut by a cutter tooth

Source: Nagendra and Mittal, 2006

In down milling (climb milling), the direction of the cutter rotation is same as the feed direction of the workpiece, as shown in Figure 2.9. The maximum thickness of the chip at the start of the cut decrease to zero thickness at the end of the cut. The cutting force tends to hold the work against the machine table. The process produces a better surface finish and dimensional accuracy. The coolant can be fed easily, chips are disposed off conveniently, thus the machined surface hasn't spoiled.



(a) (b)

Figure 2.9: Down milling operation: (a) direction of the cutter rotation and (b) the chip cut by a cutter tooth

Source: Nagendra and Mittal, 2006

2.4.3 Speed, Feed and Depth of Cut

Typical recommendations for speeds and feeds are given in Table 2.1 for roughing cuts and finishing cuts with either high-speed steel (HSS) or brazed carbide cutters based on types of workpiece. Feed per tooth also known as chip load is important to calculate the feed rate of machining, while speed is used to determine spindle speed during the milling process.

Table 2.1: Recommended cutting speeds and feeds for milling.

Material	(Bhn)	Depth of Cut (mm [in.])	Face Mill: High-speed Steel (HSS) Feed (mm/tooth [in./tooth])	Face Mill: High-speed Steel (HSS) Speed (m/min [ft/min])	Face Mill: Uncoated Cemented Carbide Feed (mm/tooth [in./tooth])	Face Mill: Uncoated Cemented Carbide Speed* (m/min [ft/min])	Plain or Slab Mill: High-speed Steel HSS Feed (mm/tooth [in./tooth])	Plain or Slab Mill: High-speed Steel HSS Speed (m/min [ft/min])
Aluminum alloys cold drawn	30–80 (500 kg)	7.62 (.300) 1.02 (.040)	0.51 (.020) 0.25 (.010)	198 (650) 366 (1,200)	0.64 (.025) 0.25 (.010)	366 (1,200) 610 (2,000)	0.41 (.016) 0.30 (.012)	259 (850) 366 (1,200)
Copper alloys cold drawn 145 to 782	50–100 R_B	7.62 (.300) 1.02 (.040)	0.46 (.018) 0.25 (.010)	122 (400) 183 (600)	0.51 (.020) 0.25 (.010)	213 (700) 396 (1,300)	0.46 (.018) 0.36 (.014)	122 (400) 191 (625)
Gray cast iron as cast Class 45 and 50	220–260	7.62 (.300) 1.02 (.040)	0.36 (.014) 0.15 (.006)	15 (50) 26 (85)	0.36 (.014) 0.18 (.007)	63 (205) 122 (400)	0.25 (.010) 0.15 (.006)	14 (45) 24 (80)
Steel hot rolled or cold drawn 1005–1025	175–225	7.62 (.300) 1.02 (.040)	0.41 (.016) 0.20 (.008)	34 (110) 58 (190)	0.41 (.016) 0.20 (.008)	95 (310) 168 (550)	0.25 (.010) 0.15 (.006)	34 (110) 56 (185)
Steel hot rolled or cold drawn 1030–1055 1525–1527	225–275	7.62 (.300) 1.02 (.040)	0.36 (.014) 0.15 (.006)	24 (80) 38 (125)	0.36 (.014) 0.18 (.007)	81 (265) 137 (450)	0.23 (.009) 0.13 (.005)	21 (70) 37 (120)
Steel Heat treated 1330–4130 5130–8630	275–325	7.62 (.300) 1.02 (.040)	0.31 (.012) 0.15 (.006)	18 (60) 31 (100)	0.25 (.010) 0.15 (.006)	72 (235) 114 (375)	0.18 (.007) 0.13 (.005)	15 (50) 27 (90)

*Notes: Speeds given are for brazed carbide teeth. For throwaway or indexable uncoated inserts, speeds may be 10–20% higher, and for coated inserts 30–50% higher. These are relatively large and strong cutters. Feeds may be less for smaller and weaker cutters, such as end mills, form cutters, and saws.

Source: Institute of Advance Manufacturing Science, 1980

The spindle speed is based on the cutter diameter because cutting speed for a mill cutter is the linear velocity of a point on the periphery of the cutter, as shown in equation 2.1 bellow.

$$n = (CS \times 1000) / \pi d \tag{2.1}$$

Where

n = spindle speed, rpm

CS = cutting speed, m/min

d = diameter of the cutter, mm

Basic milling feed (feed per tooth) is the distance the workpiece advance in the time between engagements by two successive teeth. The machine feed rate is given as follows:

$$f = f_t \times Z \times n \tag{2.2}$$

Where

f = machine feed, mm/min

f_t = cutter feed/tooth, mm/tooth

Z = number of teeth on the cutter

n = spindle speed, rpm

The actual feed is considerably less than the nominal feed per tooth for shallow cuts as shown in Figure 2.10. When the depth of cut is at least equal to the radius of the cutter, the two components of feed are equal (Schrader and Elshennawy, 2000). For end mill, depth of cut should not exceed half of the diameter of the tool in steel, but in soften metals such as aluminium, it can be more.

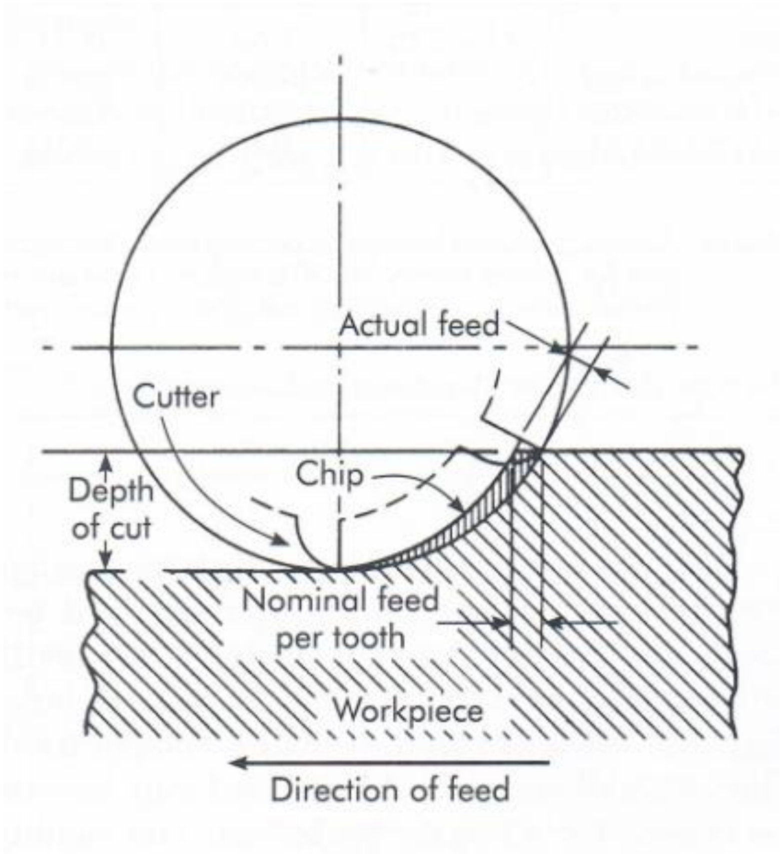


Figure 2.10: Relationship between actual and nominal milling feed

Source: Schrader and Elshennawy, 2000

2.5 FAST FOURIER TRANSFORM (FFT)

FFT is a mathematical technique to convert the signal from the time domain into the frequency domain. The signal at the detector, disability or on the display oscilloscope acoustic emission is usually the time domain signal that shows how the amplitude varies with time. When transformed into the frequency domain display shows how the amplitude varies with frequency. This view is often referred to as the signal frequency spectrum.

One line at a frequency in the frequency domain because single frequency sine wave in the time domain that will give rise sharply in the time domain which gives the spread of frequencies in the frequency domain (Edward *et al.*, 2007). Spike made by adding sine waves of all different frequencies at one point when they were all together to give while the spike at all other times they all cancel to give zero signals. Switch back from the frequency domain to time domain is the inverse FFT.

Changes the Fourier are very useful because they reveal the period of the input data and the relative strengths of any periodic components. The result means the FFT operation, periodic functions will include changing the peak is not one, but two places. However, both these components are symmetric, so it was only necessary to see one to obtain frequency information. And providing information about the frequency, the FFT can be used to apply signal processing techniques such as filtering the signal and image compression is much easier to implement in the frequency domain.

2.6 SUMMARY

Nowadays, a variety of manufacturing processes are needed to produce parts and products, used in human life every day. One of the processes is machining, removing the unwanted material from a workpiece to get it the required shape. If chatter happens during machining, the excessive vibration of the cutter and workpiece result in poor cutting, and may damage the tool and workpiece. Most commonly chatter research has focused to increase the material removal rate while avoiding the onset of chatter. The uniform mill cutter has a higher probability to occur chatter, so the irregular cutting tool was designed to suppress unwanted chatter vibration during cutting operations. Milling is a machining operation in which a work part is fed past a rotating cylindrical tool with multiple cutting edges.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

This chapter presents the overall methodology of the experiments. Research methodology indicates procedures that are planned for the research. It is to ensure that the development of the research is smooth, follow the guideline based on the objectives and get the expected result. The experimental methods and procedures are discussed clearly step by step in this chapter. In other words the methodology can be described as the framework of the research where it contains the elements of work based on the objectives and scopes of the research. The aim of this chapter is to discuss about the experiment under circumstances condition.

3.2 EXPERIMENT PROCEDURE

The experiment will be conducted based on the scopes of the project, and these will be now introduced. It should be pointed out that the majority of experiments was performed on difficult-to-machine metal, where chatter frequently encountered. Starting with the first requirement, build a single degree of freedom flexural, then using cutting stiffness and modal properties to predict chatter stability of the tools. The experiment is conducted to compare analytical prediction, and to validate chatter of variable helix and variable pitch tool results. The flow chart of methodology is shown as Figure 3.1.

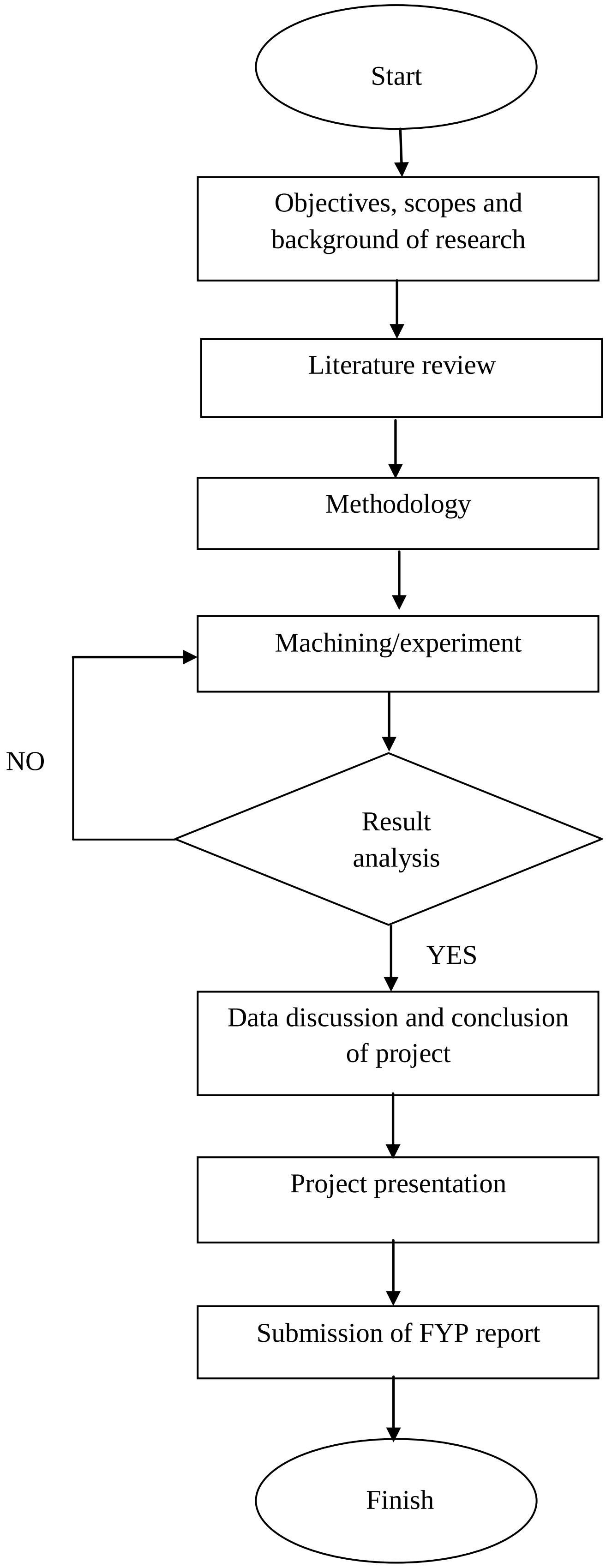


Figure 3.1: Flow chart of methodology

3.2.1 Build a Flexure

In this project, a single degree of freedom flexure as shown in Figure 3.2, have to build as the first requirement in the project. During the machining experiment to validate the chatter stability prediction, flexure will be clamped to the worktable of the machine, while the workpiece have to tight on the top of flexure.

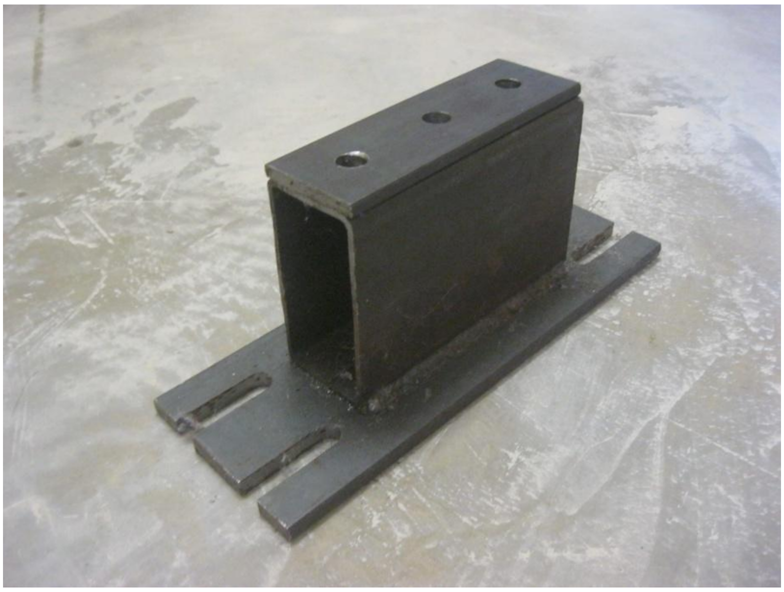


Figure 3.2: Flexure of experiment

3.2.2 Frequency Response Function (FRF)

The experimental approach involved of the impact hammer model in which the testing applied was to measure FRF for flexure and cutting tools, refer to Appendix B. The data acquisition system apparatus used was a Bruel & Kjaer model type 7539A 5/1 channel, as shown in Figure 3.3. Meanwhile, a normal force created by using a 2302-10 Meggit Hammer with vinyl tip was applied at the tool tip for an impact testing, refer to Figure 3.4, a 4507B Bruel & Kjaer accelerometer in Figure 3.5 has captured the acceleration response. It was located opposite to the hammer impact point.

Figure 3.3: Bruel & Kjaer model type 7539A 5/1 channel

Figure 3.4: 2302-10 Meggit Hammer

Figure 3.5: 4507B Bruel & Kjaer accelerometer

3.2.3 Cutting Stiffness Determination

To find the cutting stiffness of regular cutting tools, the type of tool that use is end mill cutting tool. The workpiece aluminum 7075 will be cut with a slot in the center of it. The tool will make the slot cutting on the workpiece with different feed rates. But, the spindle speed and the depth of cut will be constant.

Here, the workpiece or block of aluminum 7075 will be clamped on the Dynamometer Force (Kitsler 9257B) as shown in Figure 3.6. During the cutting process, this is before and after the tool reaches the workpiece, the signal need to be recorded by using dynamometer force.

After the experiment is done, the graphs that obtain from the computer that connected from the dynamometer force can be collected. Here, the average of cutting forces was plotted in order to get the linear regression, in this graph, the average force corresponds to the particular feed rate for each point.

Figure 3.6: Example of clamping the workpiece on dynamometer force

3.2.4 Milling Cutting Tools

The uniform milling cutting tool has a uniform helix (45^o, 45^o, 45^o, 45^o) and uniform pitch (90^o, 90^o, 90^o, 90^o) as shown in Figure 3.7(a,c). Using the optimized process, the variable milling cutter was designed to prevent a chatter condition during the machining process. The variable tool with variable helix (41^o, 53^o, 51^o, 41^o) and variable pitch (55^o, 118^o, 225^o, 360^o) as shown in Figure 3.7(b,d).

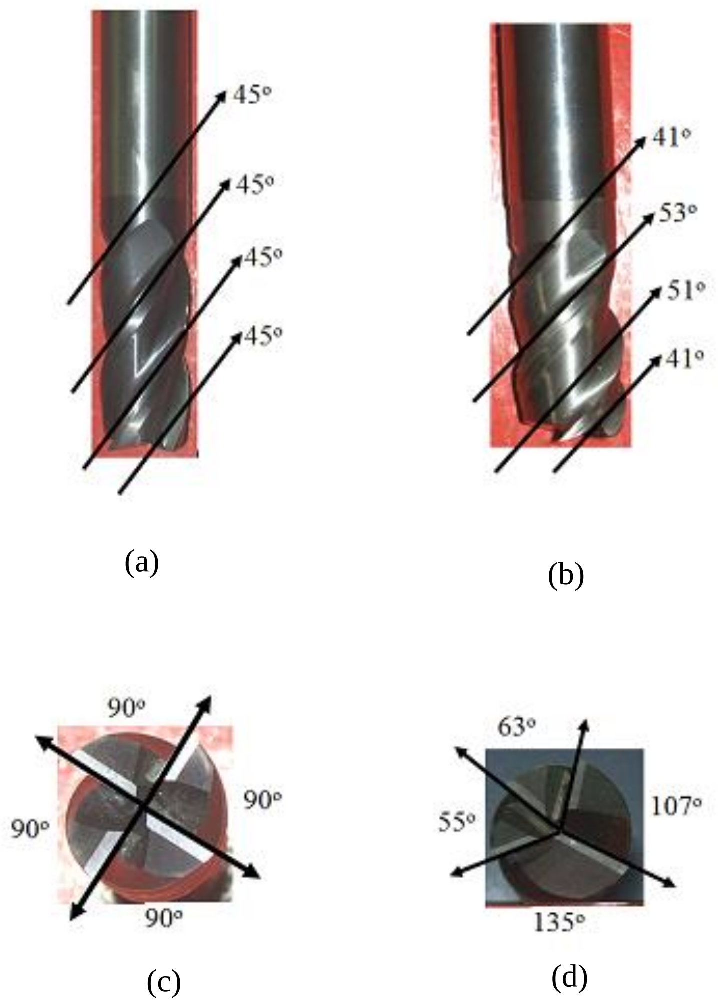


Figure 3.7: Tool geometry for experimental validation: (a) uniform helix, (b) variable helix, (c) uniform pitch and (d) variable pitch

3.2.5 Chatter Stability Prediction

Using the cutting stiffness of cutting tool and modal properties that were found before, chatter stability of the tool is predicted. Based on that data, the prediction process is using software (refer to Appendix C) that applied the semi descretization method (SDM) will give the stability lobes diagram (refer to Appendix D).

3.2.6 Preparation of Material (Workpeice)

After finishing chatter stability prediction, the project continued by preparing the materials which are aluminium that available at FKM Laboratory. In this stage, band saw machine as shown in Figure 3.8, have been used for this purposed to cut aluminum 7075 bars with dimension of 150 x 50 x 30 mm^3 each (Figure 3.9). The quantities of workpieces are based on the points on the stability lobes diagram that wanted to be tested.

Figure 3.8: Band Saw Machine

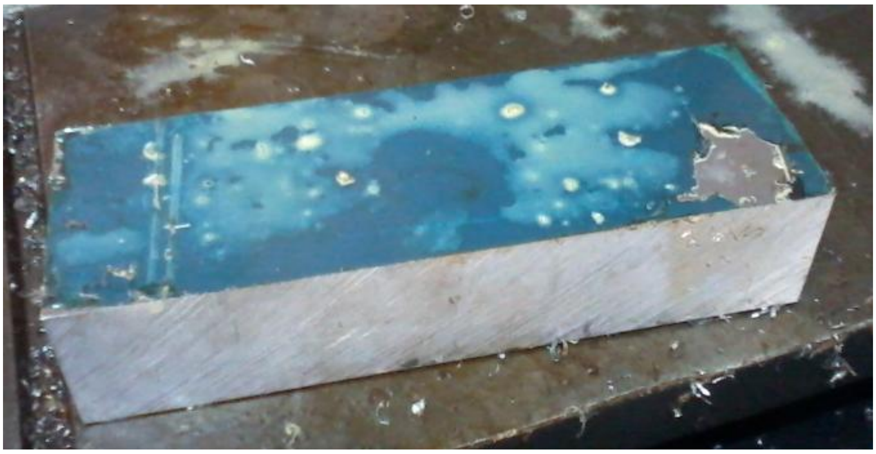


Figure 3.9: Aluminium 7075 specimen

3.2.7 Machining Experiment

The cutting processes were conducted to compare chatter analytical predicted done using SDM. The critical depth of cut from the graph of stability lobes will be tested by cutting experiment to know the chatter stability, then to validate the prediction before.

The machining was performed on a Haas VF6 Milling Machine, as shown in Figure 3.10. Milling process at 25 percent radial immersion using a 20 mm diameter 4 flute end mill cutting tool will be machining the workpiece that mounted on flexure, while feed per tooth is 0.08 mm per tooth. Refer to Appendix E for Haas VF6 Milling Machine specifications.

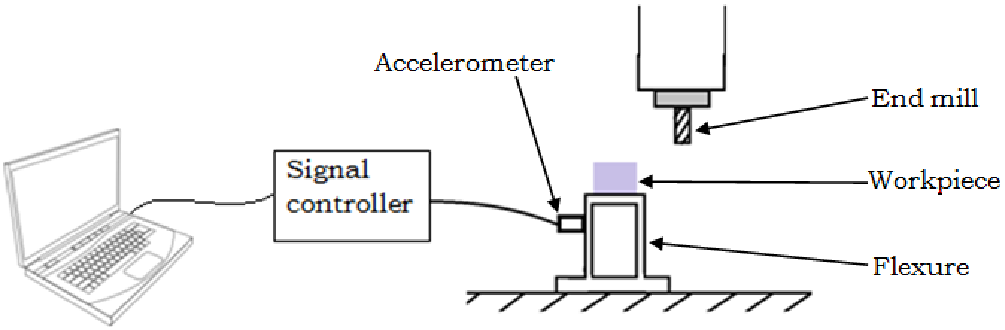
The cutting tool that used either regular tool or variable tool has implemented the procedure previously. A set of spindle speed and axial depth of cut was tested to identify the cutting condition, refer to Appendix F. During cutting experiment, the vibration signal was recorded using an accelerometer. These two parameters are selected based on the point in the stability lobes diagram that wanted to be tested.

Figure 3.10: Haas VF6 Milling Machine

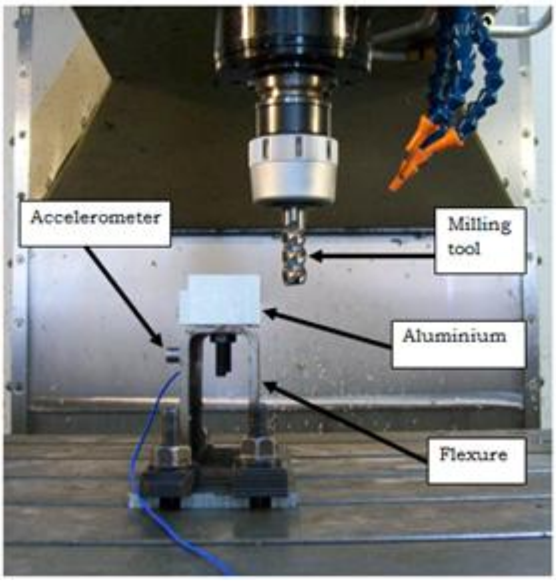
During the experiment, the acceleration response was captured by piezoelectric accelerometer (PCB 352C03), refer to Figure 3.11, which located on the flexure and connected to a National Instrument High Speed USB Carrier NI USB-9162 (refer to Figure 3.12) and laptop. Figure 3.13 is show the experiment setup. Refer to Appendix G for piezoelectric accelerometer (PCB 352C03) specifications. After the experiment is done, the graphs of FFT spectrum and acceleration signal that obtain on the computer that connected to the accelerometer can be collected.

Figure 3.11: Piezoelectric accelerometer (PCB 352C03)

Figure 3.12: National Instrument High Speed USB Carrier NI USB-9162



(a)



(b)

Figure 3.13: Cutting experiment setup: (a) schematic diagram and (b) accelerometer location

3.3 RESULTS ANALYSIS

The results obtained from the machining experiment using CNC vertical milling machine will be defined, and classify it vibration condition. The results used to compare chatter analytical prediction and to validate the chatter stability of variable tool results. The others findings or journals will be used as the comparison to the results to make sure that the result is acceptable and follow the theoretical behavior.

Conclusion and recommendation will be made based on the result and discussion that being got from the machining experiments. The conclusion becomes as a summary of overall procedures of research, and recommendation will be suggested to improve any weakness founded during the experiment.

CHAPTER 4

RESULTS AND ANALYSIS

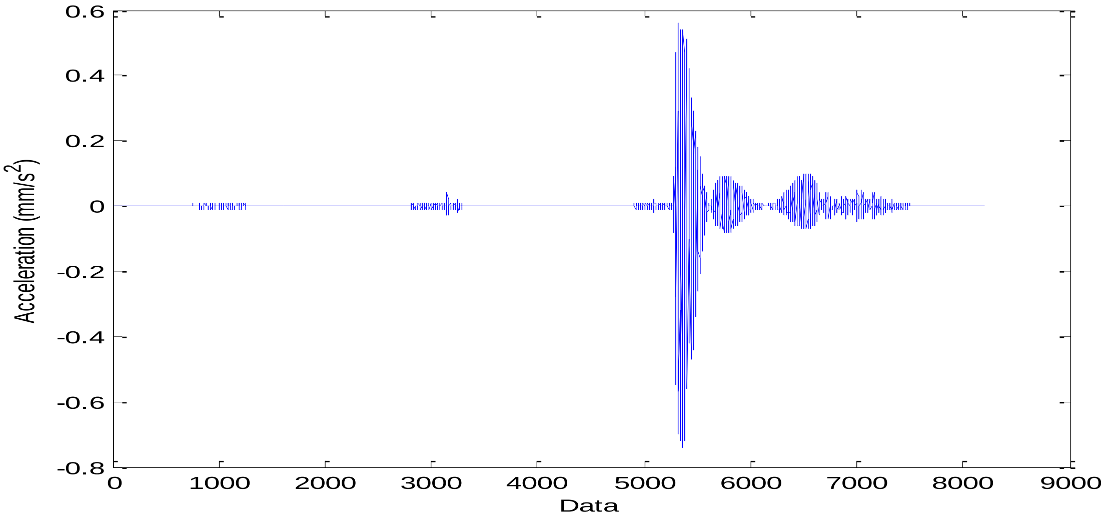
4.1 INTRODUCTION

This chapter generally discussed about the results and the analysis that obtained throughout the experimental validation for chatter stability prediction. The performance of cutting tools, uniform and variable, will be investigated in the experiment. The experiment will show where a highly flexible workpiece is used to induce some chatter condition, while the variable tool is used to avoid chatter from happen. Then, the machining experimental results will be compared with the prediction graphs of tools.

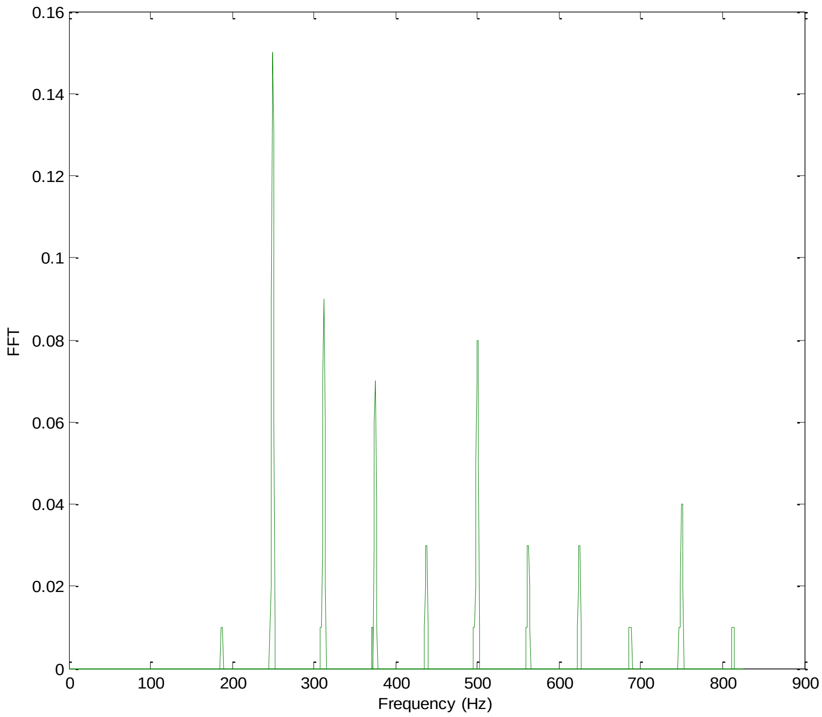
4.2 CHATTER STABILITY IDENTIFICATION

The FFT spectrum and acceleration signals were measured for performance of uniform and variable tools in down-milling machining experiment. For uniform tool, the cutting tests were carried out in 5 cases: A (4750 rpm, 0.25 mm), B (4750 rpm, 0.75 mm), C (3750 rpm, 1.0 mm), D (4250 rpm, 1.0 mm) and E (5250 rpm, 1.25 mm). For variable cutting tool where variable helix and variable pitch were used, case F (5000 rpm, 1.25 mm) is the example that present result of the optimize cutter performance.

The cases A, C and F as shown in Figures 4.1, 4.2 and 4.3, respectively, represent the stable condition and chatter free cutting results. In the acceleration graph, there is a small acceleration variable with a value under 10^{-3} m/s^2. In FFT graph, these frequencies are lower than the FRF of flexure, which related to cutting forces for each tooth beating the workpiece.

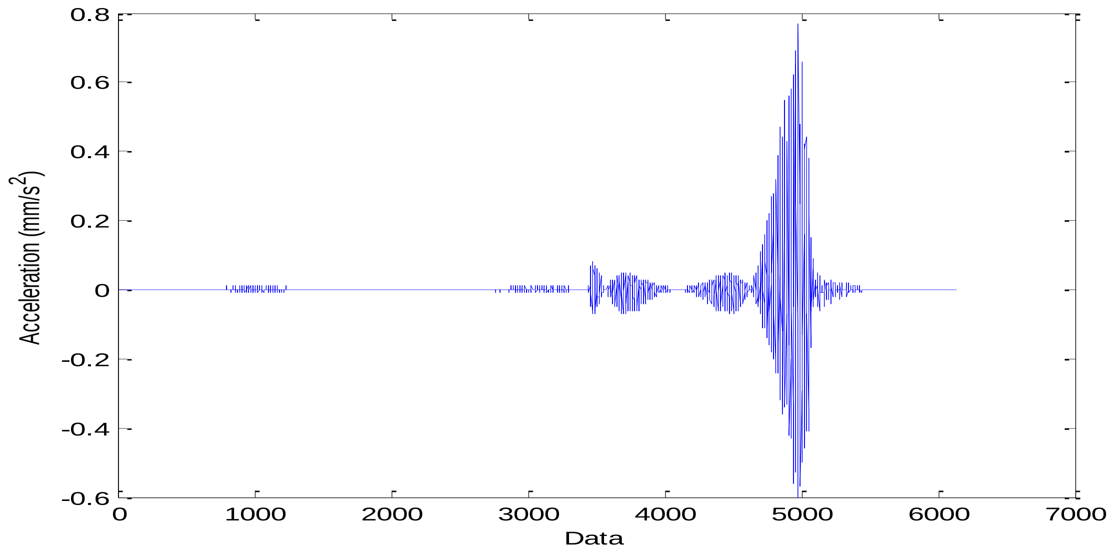


(a)

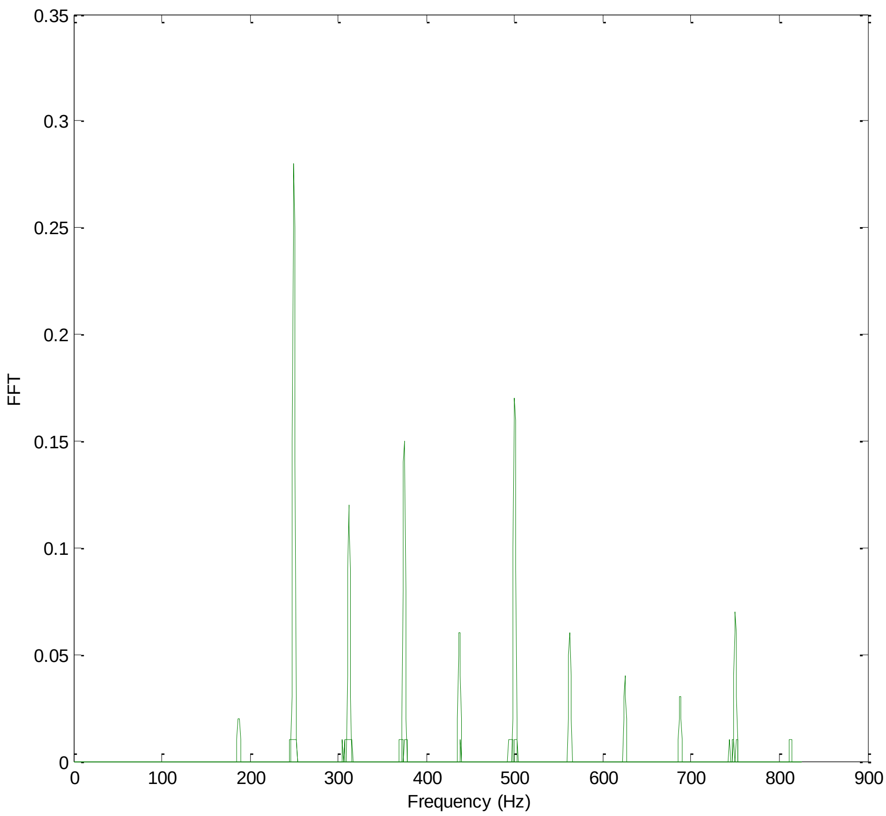


(b)

Figure 4.1: Experiment result from point A (4750 RPM, 0.25 mm): (a) acceleration signal and (b) FFT spectrum

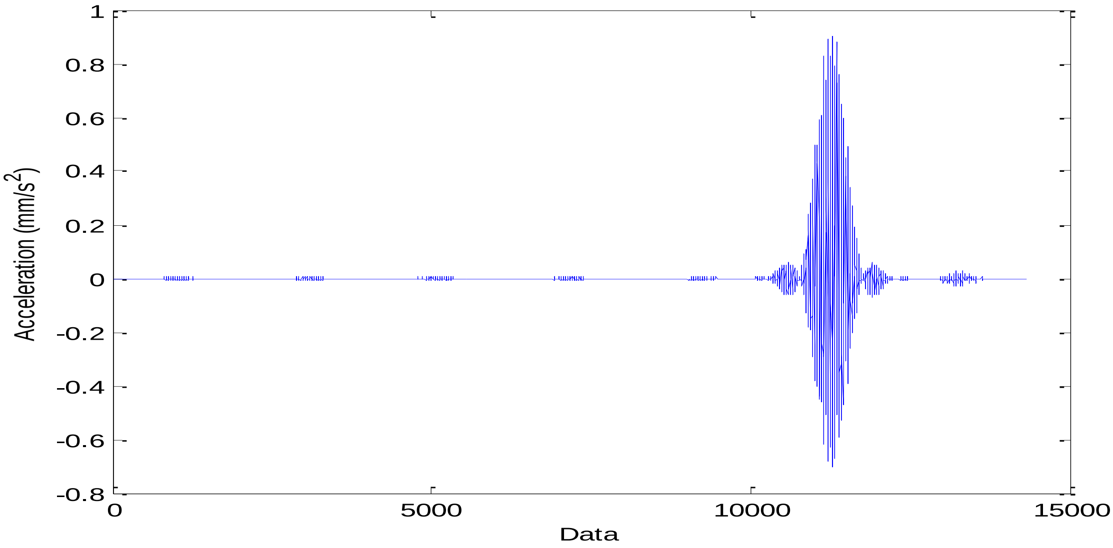


(a)

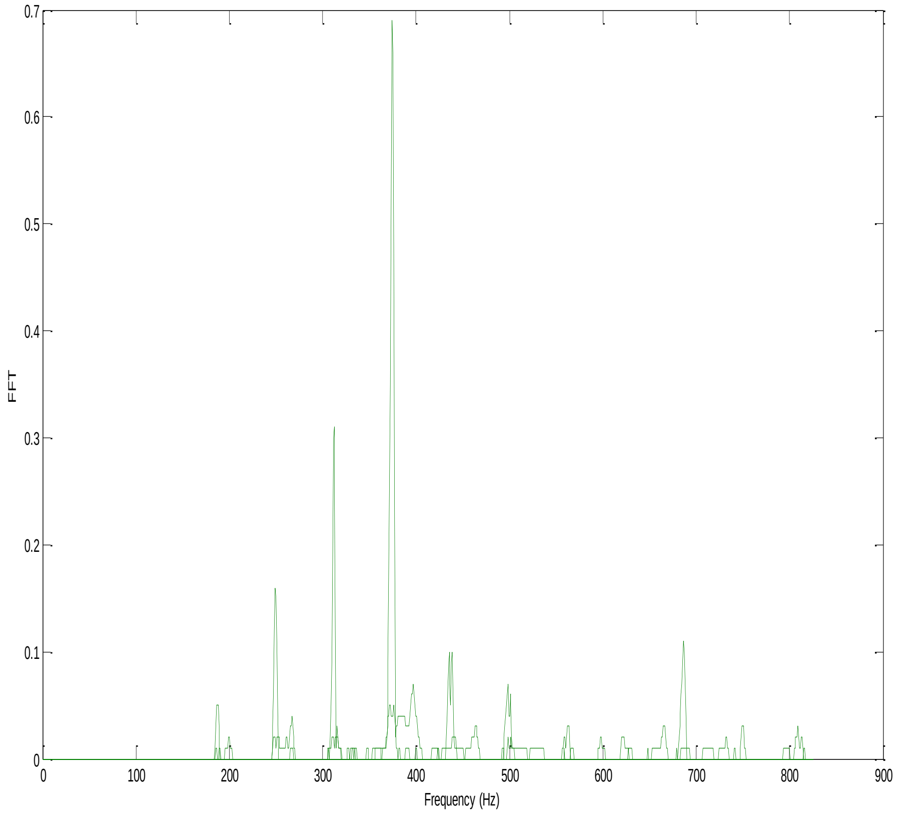


(b)

Figure 4.2: Experiment result from point C (3750 rpm, 1.0 mm):
(a) acceleration signal and (b) FFT spectrum



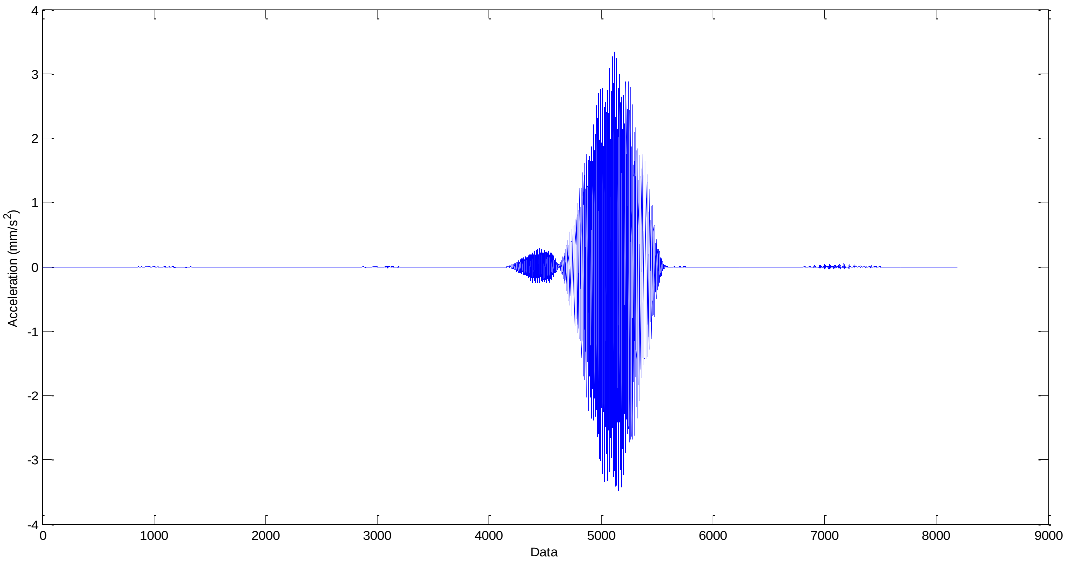
(a)



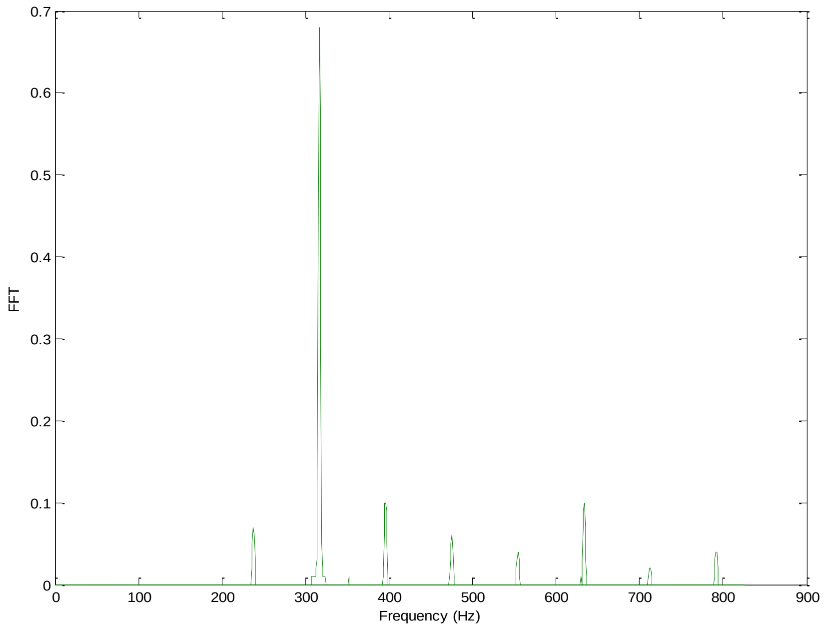
(b)

Figure 4.3: Experiment result from point F (5000 rpm, 1.25 mm): (a) acceleration signal and (b) FFT spectrum

The cases B and D as shown in Figures 4.4 and 4.5, respectively, represent the unstable chatter vibration in machining experiment. Based on the FFT spectrum, the chatter frequency was close to FRF of flexure. The acceleration variance is greater than 10^{-3} m/s^2, indicator for the chatter vibration condition.

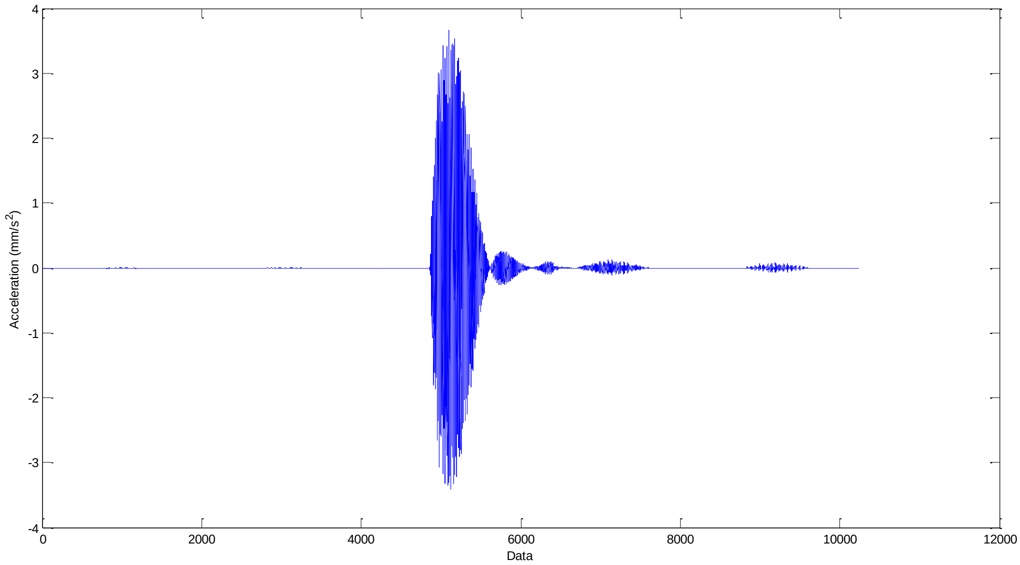


(a)

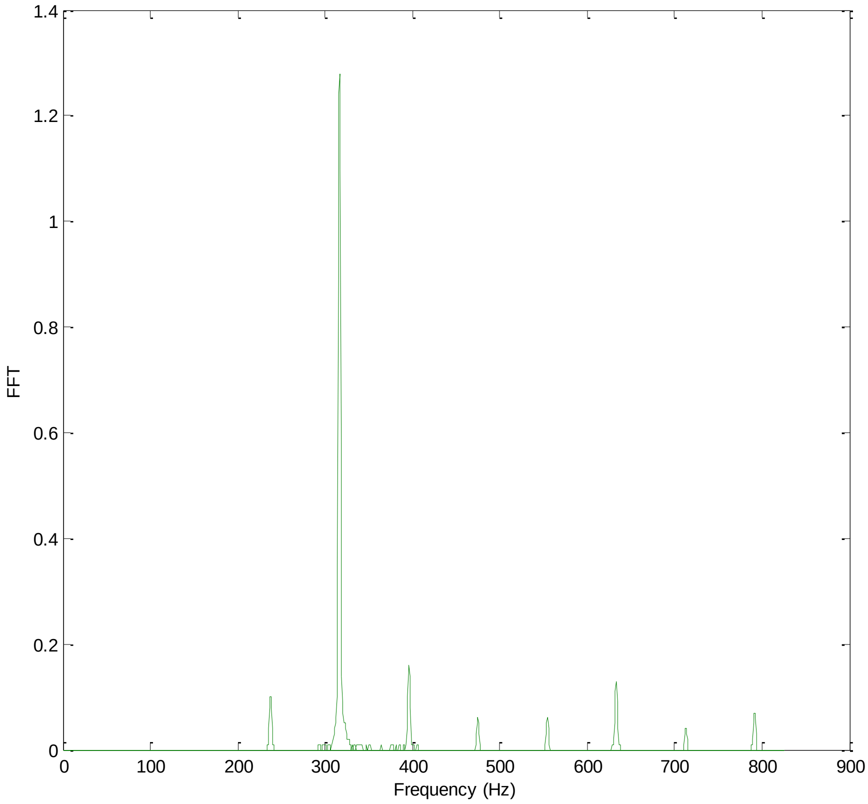


(b)

Figure 4.4: Experiment result from point B (4750 rpm, 0.75 mm): (a) acceleration signal and (b) FFT spectrum



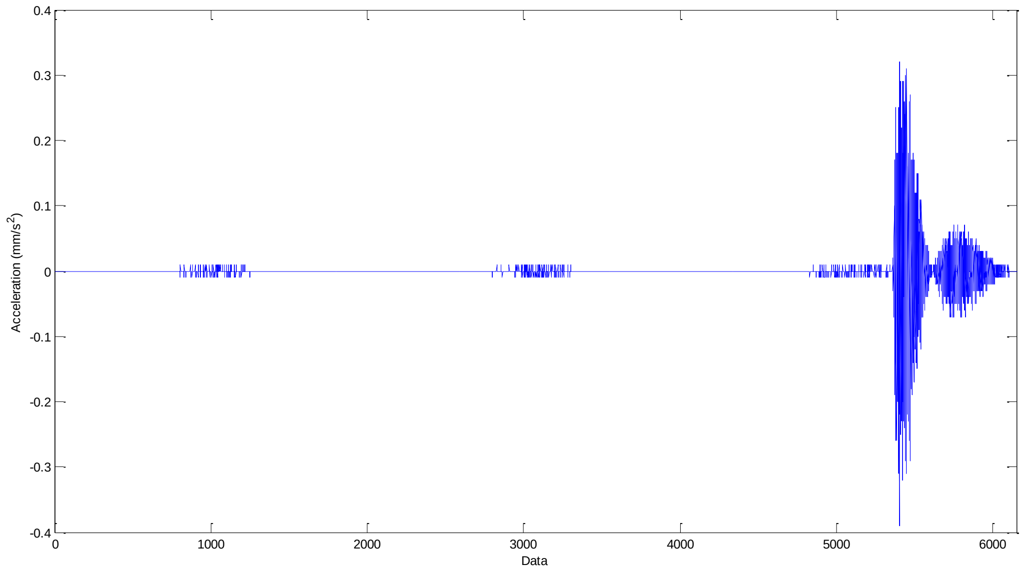
(a)



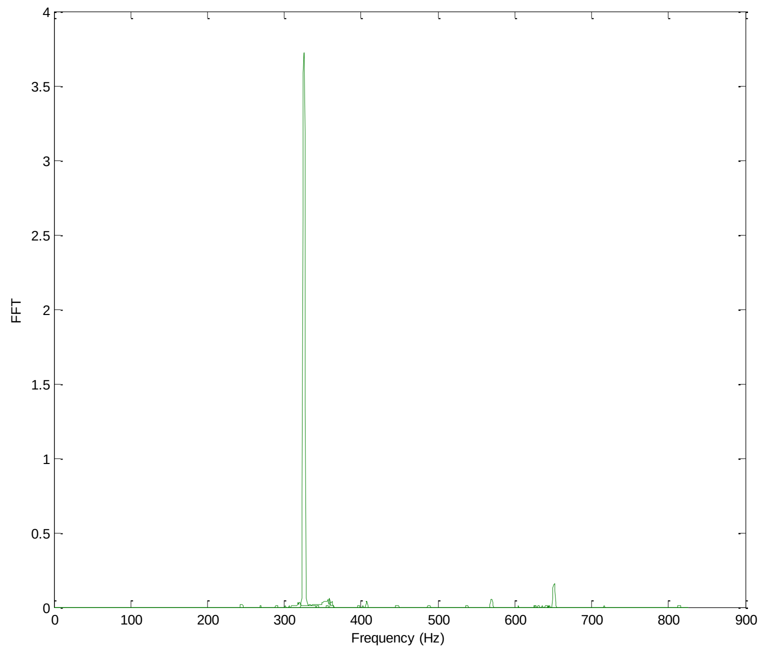
(b)

Figure 4.5: Experiment result from point D (4250 rpm, 1.0 mm): (a) acceleration signal and (b) FFT spectrum

Case E presented the condition where condition is not chatter or stable vibration, as shown in Figure 4.6. The acceleration variance is less than 10^{-3} mm/s^2, but the FFT spectrum has a quite high of value, where the resonance maybe happen during machining test at high spindle speed.



(a)



(b)

Figure 4.6: Experiment result from point E (5250 rpm, 1.25 mm):
(a) acceleration signal and (b) FFT spectrum

4.3 CHATTER STABILITY COMPARISON

Based on the FFT spectrum and acceleration signal, vibration condition during experiment for each case was identified. Both uniform tool and variable tool were compared its theoretical prediction and machining experimental results, in order to present their chatter stability diagrams.

The chatter stability diagram for uniform cutting tool was predicted using SDM. The results machining at 25 percent radial depth of cut (radial immersion) of 20 mm tool's diameter was superimposed with stability diagram, as shown in Figure 4.7. Based on the stability lobe, it can be understood that there is a chatter region (unstable condition) at high axial depth of cut, where the critical depth of cut is about 0.5 mm. This critical line informed the maximum depth of cut before chatter happens.

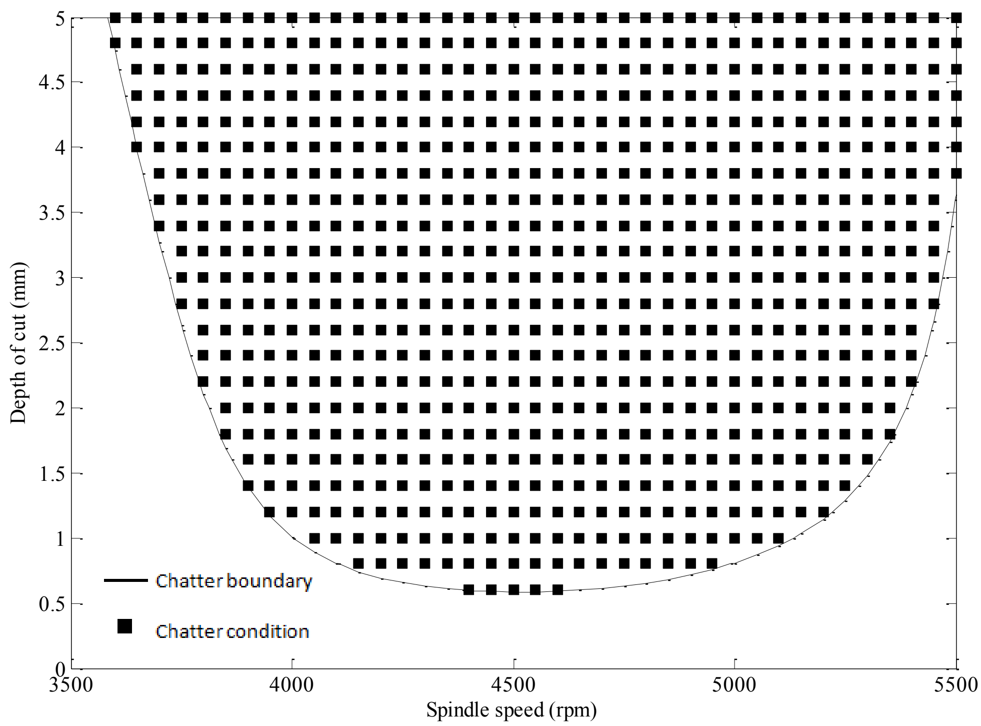


Figure 4.7: Chatter stability prediction diagram for uniform cutting tool

The comparison in Figure 4.8 show that there are good agreement between predicted stability and cutting experiment for the down-milling operation using uniform 4 flutes cutting tool. Stable conditions were shown outside the boundary of chatter region. Acceleration variance and FFT spectrum were used as the indicators to identify the vibration condition, either stable or chatter happen.

The undefined vibration condition was detected at high spindle speed, where resonance probably happened was indicated by symbol ' $\triangle$ ' in stability diagram. Its mean about 0.5 mm is the critical depth of cut for uniform cutting tool, experimentally confirmed.

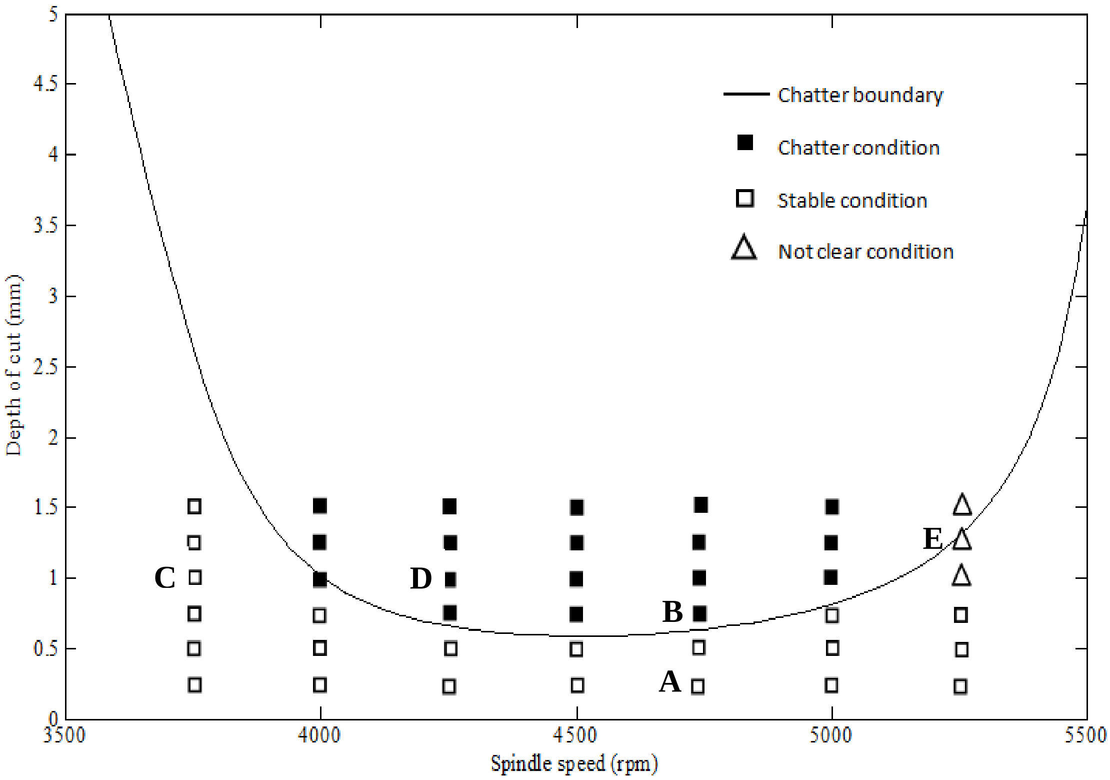


Figure 4.8: Experimental validation results for uniform cutting tool

The optimized cutting tool was predicted to totally suppress chatter, as a result of the effectiveness of optimization variable tool (helix and pitch), as shown in Figure 4.9. This prediction graph imagines that the variable tool has ability to machining the workpiece in range of spindle speed 3500 to 5500 rpm without facing any chatter vibration conditions.

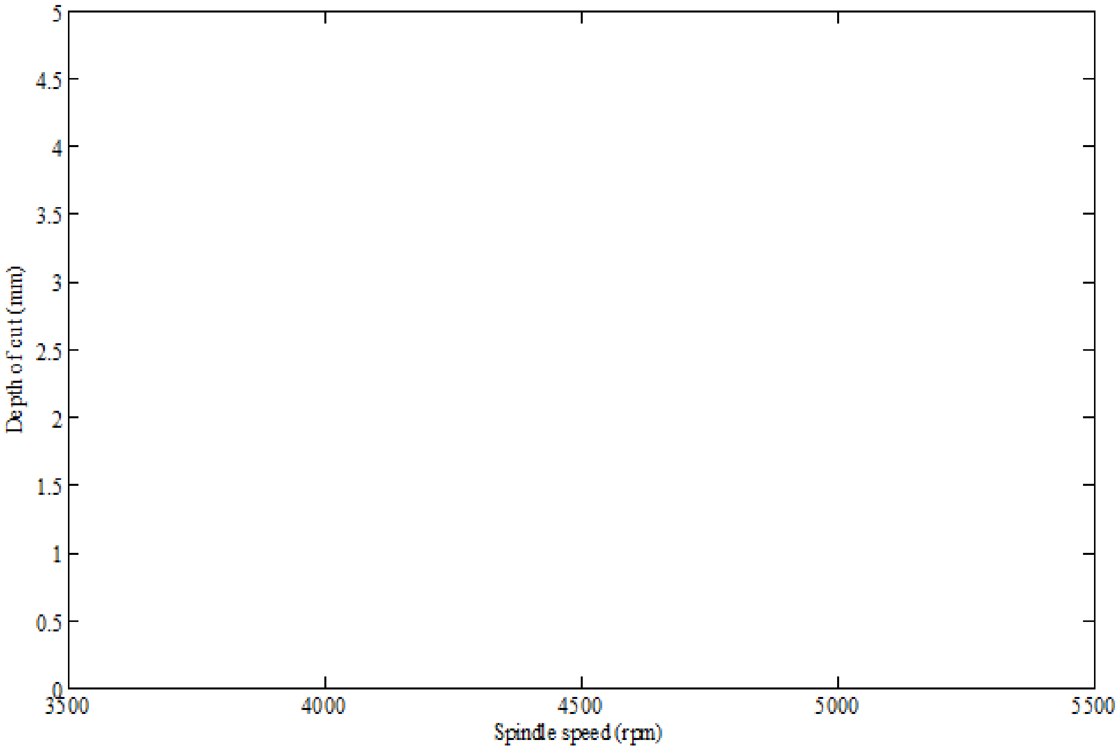


Figure 4.9: Chatter stability prediction diagram for variable cutting tool

Machining experiment tests show the stability results for the variable tool, as shown in Figure 4.10. There are no chatter vibration conditions during the machining process until 1.5 mm depth of cut. That's mean 0.5 mm is not the critical depth of cut any more, compared with the uniform cutter, meaning it was minimized by optimize tool.

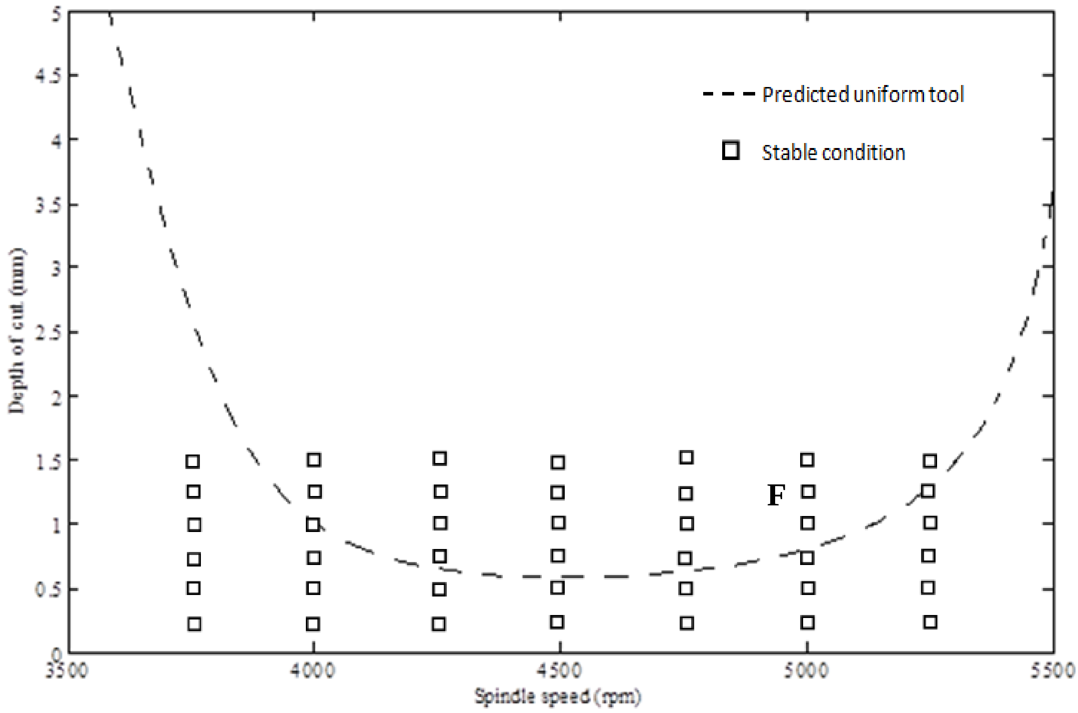


Figure 4.10: Experimental validation results for variable cutting tool

4.4 SUMMARY

The chatter stability diagram for regular and variable cutting tool that used in machining were validated in cutting experiment. The vibration conditions of machining were identified using indicators, acceleration signals and FFT spectrum. The comparisons showed there were good agreement between the predictions using SDM and machining results.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

In conclusion, all the objectives of the research, ‘Experimental Validation for Chatter Stability Prediction’ are achieved. Firstly, the project is to prepare specimens of material aluminium 7075. The material for machining experiment was cut using the band saw machine according to dimension of 150 x 50 x 30 mm^3 each.

The second objective is to validate chatter stability prediction with cutting experiment. Using the uniform and variable tool, the cutting experiment of down-milling machining with 5 mm radial immersion was conducted to validate the chatter stability diagram, where predicted using SDM. The chatter condition was identified when analysis the vibration signals and FFT spectrum, results of machining.

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The third objective of the project is to compare the chatter stability of regular and variable milling tool. Based on the result and discussion previously, it showed that a good agreement between prediction and cutting experiment for uniform tool in milling machining at near of critical depth of cut. For variable cutting tool, experiment results shown that the critical depth of cut have the improvement (higher than 0.5 mm) caused by the optimized cutter. It is also shown that the variable tool is more capability for machining without occurring chatter vibration compared to the regular tool.

By the information from this research, the optimum machining aims to maximize the material removal rate, while maintaining a sufficient stability margin to assure the surface quality can be achieved. This can be done by using a suitable geometry cutting tool and combination between the spindle speed and depth of cut in machining to avoid the chatter condition, prevent the poor surface finish and damage of tool and workpiece.

5.2 RECOMMENDATIONS

There is always room for further improvements for every study and researches that has been done. For further improvements, there are several suggestions that could be implanted when running this experimental validation research next time. Firstly, the next researchers can select more parameters and levels when running the experiment. It can be helping to reduce the errors occur and also can lead to get better accuracy. Secondly, for variable tool experimental validation, cutting test can be conducted to have determined the critical depth of cut. In comparison to the regular tool, the improvement in critical depth of cut can be shown. Thirdly, in order for better analysis results, a Hall-effect probe can be used to capture a periodic pulse signal matching the tool revolution. Once per revolution sample (1/Rev) and its cycle delay, Poincare diagrams was plotted.

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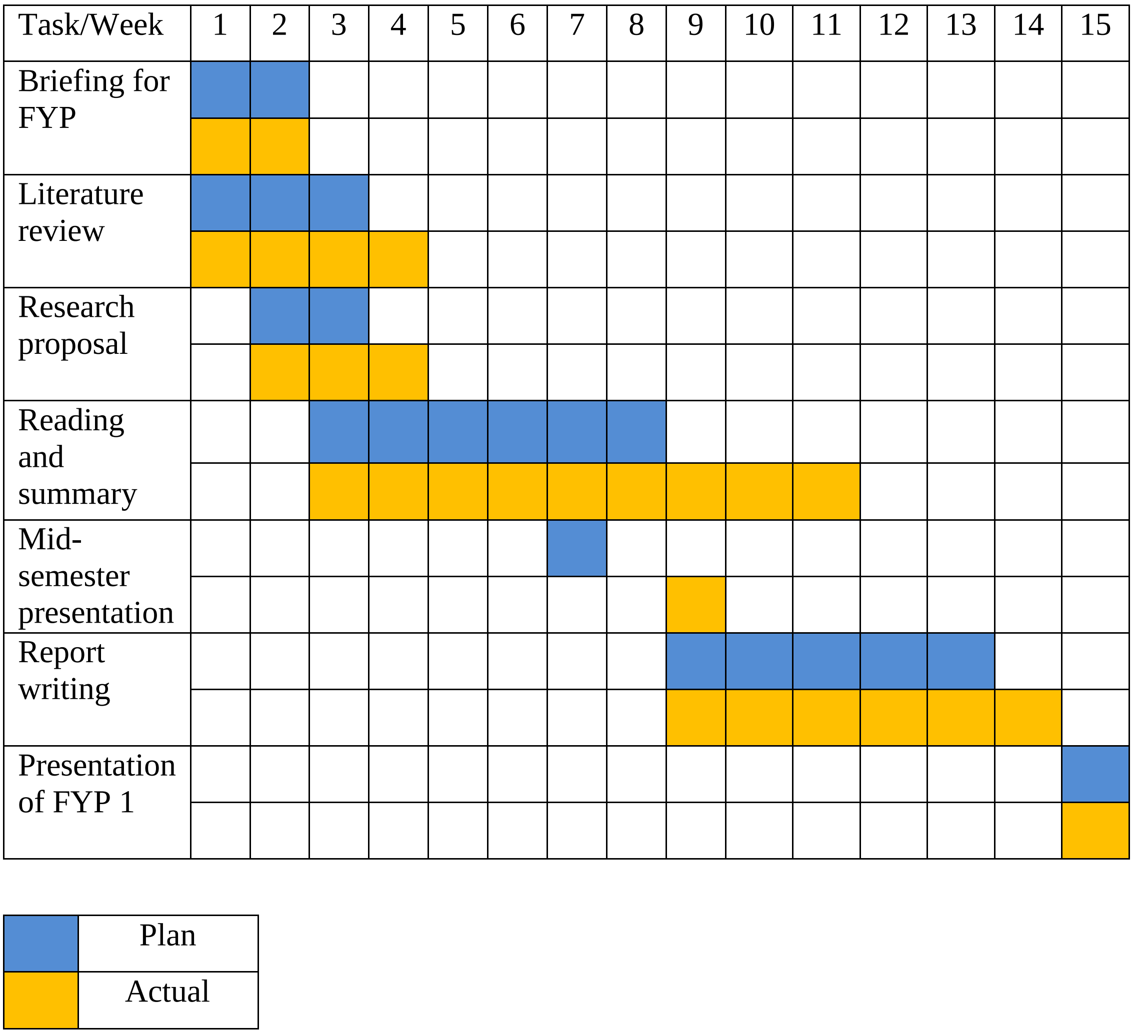
APPENDIX A

GANTT CHART

A1: FYP 1



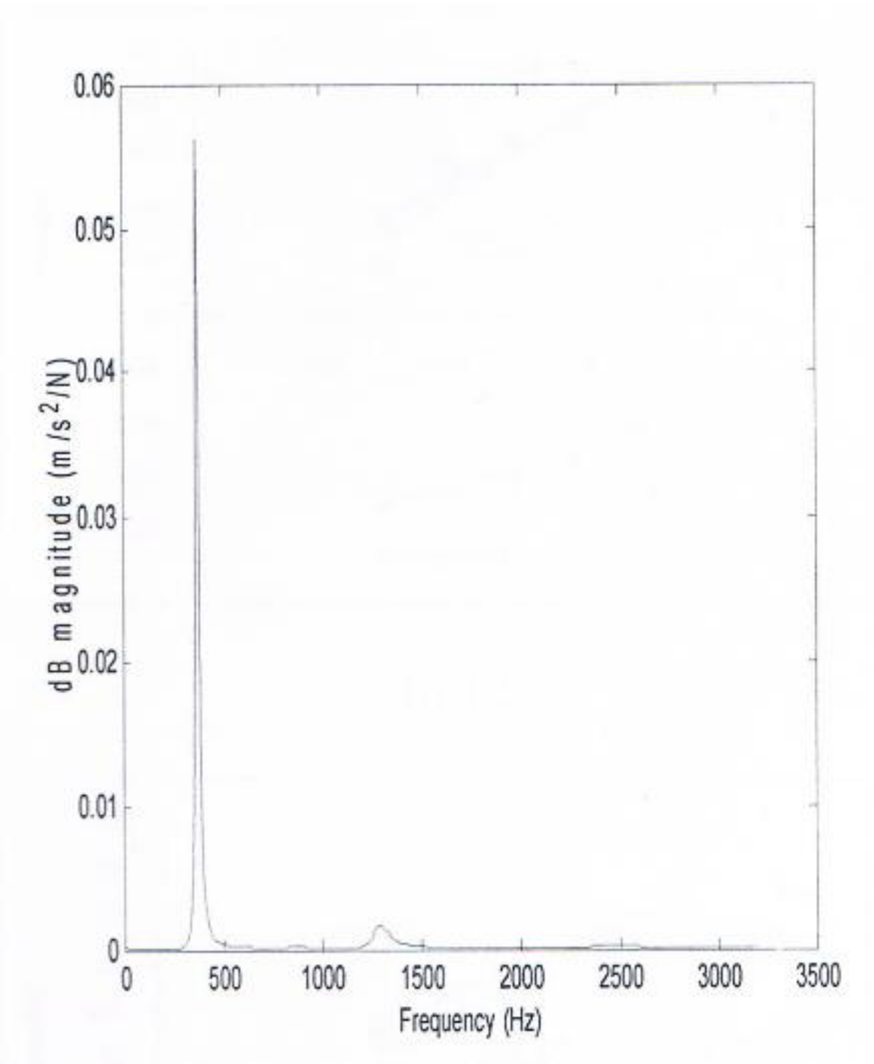
A2: FYP 2

Tasks/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Machine															
training															
Prepare															
specimens															
Cutting															
experiment															
Analysis															
results															
Report															
writing															
Presentation															
of FYP 2															

	Plan
	Actual

APPENDIX B

FREQUENCY RESPONSE FUNCTION OF FLEXURE



Source: Shaharun *et al.*, 2011

APPENDIX C

MATLAB CODE FOR CHATTER STABILITY PREDICTION

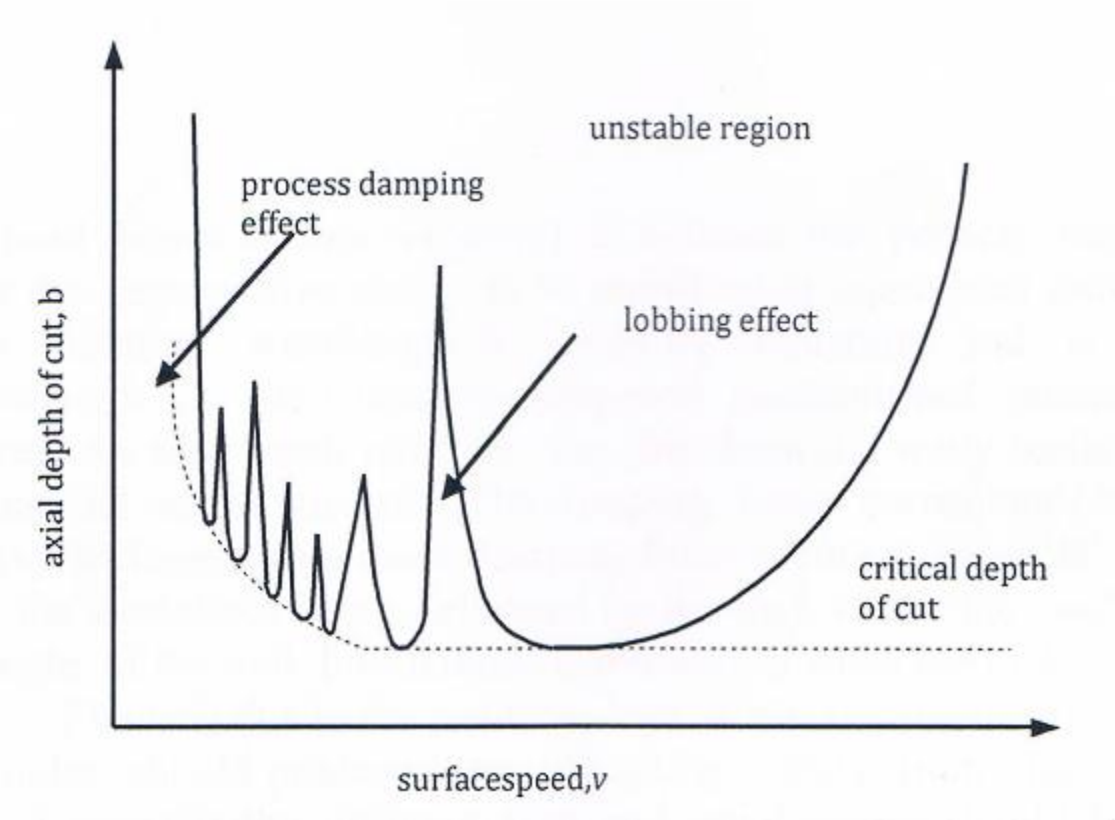
File name: run_Flexure_varHelix_4f

```
%runs the example fig 7(c) in islands paper:-
% Patel,Mann, Young, 'unchartred islands of chatter instability in
% milling', IJMTM, in press.
% for a variable helix tool
%% Set figure defaults:
set(0,'defaulttextfontname','Times','defaulttextfontsize',10,'defaul
taxesfontsize',12,'defaultAxesFontName','Times')
%% modal parameters and frequency response functions:
dataX=[]
dataX.mass=1.41;
dataX.fn=376;
dataX.zeta=0.00334;
sysX=modal2ss(dataX);
dataY=dataX;
sysY=modal2ss(dataY);
sysY.c=0*sysY.c;
sysY.d=0*sysY.d;

%% Cutting parameters:
Kt=994e6;
Kn=742e6;
Kr=Kn/Kt;
rpms=[1000:100:8000];
deltab=0.00025;
bmax=0.01;
bdiv=bmax/deltab;
bs=deltab:deltab:bmax;
radius=3/4*0.0254/2
helixV=[43 44 48]/180*pi;
helix=45/180*pi;
Phi=fluteangles([90 180 270 360]/180*pi,helix,radius,0:deltab:bmax-
deltab);
PhiV=fluteangles([84 305 360]/180*pi,helixV,radius,0:deltab:bmax-
deltab);
mode='down';
radimm=0.25;



%% no iterations
iters=500;
%% The calculations - semi discrete variable pitch:
tic;[rpmvSD,blimvSD,wlimvSD,depangvSD,tmp,zvSD,tmp,maevSD]=...

chatzSD(sysX,0,Kr*Kt,Kt,mode,radimm,Phi,deltab,iters,rpms);t_chatzSD
v=toc
%% plotting

[con,han]=contour(rpms,bs*1000,abs(maevSD)',[1 1],'k-');
```

```
set(han,'lines','-');

hold on
xlabel('Spindle speed (rpm)');ylabel('Depth of cut (mm)');title('');
set(gca,'xlim',[rpms(1) rpms(end)],'ylim',[0 bs(end)*1000])
%% optional individual plotting
 indH=abs(maevSD)'>1 & imag(maevSD)'>0;
 indF=abs(maevSD)'>1 & real(maevSD')<0 & ~indH;
 indC=abs(maevSD)'>1 & real(maevSD')>0 & ~indH;
 [rpmsm,bsm]=meshgrid(rpms,bs);
 plot(rpmsm(indH),1000*bsm(indH),'ks','markerfacecol','k');
 plot(rpmsm(indF),1000*bsm(indF),'rv','markerfacecol','r');
 plot(rpmsm(indC),1000*bsm(indC),'go','markerfacecol','g');
```

APPENDIX D

CHATTER STABILITY LOBES DIAGRAM



Source: Shaharun *et al.*, 2011

APPENDIX E

HAAS VF6 MILLING MACHINE SPECIFICATIONS

TRAVELS	S.A.E.	Metric
X Axis	64 "	1626 mm
Y Axis	32 "	813 mm
Z Axis	30 "	762 mm
Spindle Nose to Table (~ min)	5 "	127 mm
Spindle Nose to Table (~ max)	35 "	889 mm
TABLE	S.A.E.	Metric
Length	64 "	1626 mm
Width	28 "	711 mm
T-Slot Width	5/8 "	16 mm
T-Slot Center Distance	4.92 "	125.0 mm
Number of Std T-Slots	5	
Max Weight on Table (evenly distributed)	4000 lb	1814 kg
SPINDLE	S.A.E.	Metric
Max Rating	30 hp	22.4 kW
Max Speed	7500 rpm	7500 rpm
Max Torque	450 ft-lb @ 500 rpm	610 Nm @ 500 rpm
Drive System	2-Speed Geared Head	2-Speed Geared Head
Gearbox Standard	Gearbox Standard	Gearbox Standard
Taper	CT or BT 50	CT or BT 50
Bearing Lubrication	Air/Oil Injection	
Cooling	Liquid Cooled	
FEEDRATES	S.A.E.	Metric
Rapids on X	540 in/min	13.7 m/min
Rapids on Y	600 in/min	15.2 m/min
Rapids on Z	600 in/min	15.2 m/min
Max Cutting	500 in/min	12.7 m/min
AXIS MOTORS	S.A.E.	Metric
Max Thrust X	5600 lb	24910 N
Max Thrust Y	5600 lb	24910 N
Max Thrust Z	5600 lb	24910 N
TOOL CHANGER	S.A.E.	Metric
Type	SMTC	SMTC
Capacity	30+1	
Max Tool Diameter (adjacent empty)	10 "	254 mm
Max Tool Diameter (full)	4 "	102 mm
Max Tool Length (from gage line)	16 "	406 mm
Max Tool Weight	30 lb	13.6 kg
Tool-to-Tool (avg)	4.2 sec	4.2 sec
Chip-to-Chip (avg)	6.3 sec	6.3 sec

Source: Haas Automation Incorporation, 2011

APPENDIX F

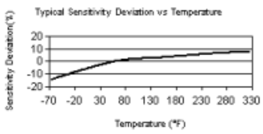
CNC CODE FOR MILLING PROCESS

```
O02121 ;
G21 ;
G00 G17 G40 G49 G80 G90 ;
M08 ;
M06 T2 ;
G90 G54 Y20. X5. ;
S3750 M03 ;
G43 H02 Z2. ;
M03 Z-1. F343. ;
G01 X5. Y-20. F1200. S4000 ;
G01 X5. Y-40. F1280. S4250 ;
G01 X5. Y-60. F1360. S4500 ;
G01 X5. Y-80. F1440. S4750 ;
G01 X5. Y-100. F1520. S5000 ;
G01 X5. Y-120. F1600. S5250 ;
G01 X5. Y-180. F1680. ;
G80 M09 ;
M05 ;
G90 G00 Z100 ;
M00 ;
```

APPENDIX G

PIEZOELECTRIC ACCELEROMETER (PCB 352C03) SPECIFICATIONS

Model Number 352C03	ACCELEROMETER, ICP®		Revision E ECN #: 25274
Performance	**ENGLISH**	**SI**	
Sensitivity (±10 %)	10 mV/g	1.02 mV/(m/s²)	
Measurement Range	±500 g pk	±4900 m/s² pk	
Frequency Range (±5 %)	0.5 to 10000 Hz	0.5 to 10000 Hz	
Frequency Range (±10 %)	0.3 to 15000 Hz	0.3 to 15000 Hz	
Resonant Frequency	≥50 kHz	≥50 kHz	
Broadband Resolution (1 to 10000 Hz)	0.0005 g rms	0.005 m/s² rms	[1]
Non-Linearity	≤1 %	≤1 %	[3]
Transverse Sensitivity	≤5 %	≤5 %	
Environmental			
Overload Limit (Shock)	±5000 g pk	±49000 m/s² pk	
Temperature Range (Operating)	-65 to +250 °F	-54 to +121 °C	[5]
Base Strain Sensitivity	0.003 g/με	0.029 (m/s²)/με	[1]
Electrical			
Excitation Voltage	18 to 30 VDC	18 to 30 VDC	
Constant Current Excitation	2 to 20 mA	2 to 20 mA	
Output Impedance	≤100 Ohm	≤100 Ohm	
Output Bias Voltage	7 to 12 VDC	7 to 12 VDC	
Discharge Time Constant	1.0 to 2.5 sec	1.0 to 2.5 sec	
Settling Time (within 10% of bias)	<10 sec	<10 sec	
Spectral Noise (1 Hz)	110 μg/√Hz	1080 (μm/sec²/√Hz	
Spectral Noise (10 Hz)	25 μg/√Hz	245 (μm/sec²/√Hz	[1]
Spectral Noise (100 Hz)	8 μg/√Hz	78 (μm/sec²/√Hz	[1]
Spectral Noise (1 kHz)	4 μg/√Hz	39 (μm/sec²/√Hz	[1]
Physical			
Size (Height)	0.62 in	15.7 mm	
Weight	0.20 oz	5.8 gm	[1]
Sensing Element	Ceramic	Ceramic	
Size (Hex)	0.44 in	11.2 mm	
Sensing Geometry	Shear	Shear	
Housing Material	Titanium	Titanium	
Sealing	Hermetic	Hermetic	
Electrical Connector	10-32 Coaxial Jack	10-32 Coaxial Jack	
Electrical Connection Position	Side	Side	
Mounting Thread	10-32 Female	10-32 Female	
Mounting Torque	10 to 20 in-lb	113 to 226 N-cm	



CE[4]

All specifications are at room temperature unless otherwise specified.

Optional Versions (Optional versions have identical specifications and accessories as listed for standard model except where noted below. More than one option maybe used.)

HT - High temperature, extends normal operation temperatures			[5]
Frequency Range (±5 %)	5 to 10000 Hz	5 to 10000 Hz	
Frequency Range (±10 %)	3 to 15000 Hz	3 to 15000 Hz	
Temperature Range (Operating)	-65 to +325 °F	-54 to +163 °C	
Excitation Voltage	22 to 30 VDC	22 to 30 VDC	
Discharge Time Constant	0.1 to 0.3 sec	0.1 to 0.3 sec	
Spectral Noise (1 Hz)	200 μg/√Hz	1962 (μm/sec²/√Hz	[1]
Spectral Noise (10 Hz)	30 μg/√Hz	294 (μm/sec²/√Hz	[1]
Output Bias Voltage	10 to 15 VDC	10 to 15 VDC	[2]
Supplied Accessory: Model ACS-68 Single Axis Amplitude Response Calibration from 5 Hz to upper 5% plotted on dB scale replaces Model ACS-1			
J - Ground Isolated			
Frequency Range (5 %)	9000 Hz	9000 Hz	
Frequency Range (10 %)	14000 Hz	14000 Hz	
Resonant Frequency	≥40 kHz	≥40 kHz	
Electrical Isolation (Base)	>10⁸ Ohm	>10⁸ Ohm	
Size (Hex x Height)	0.44 in x 0.67 in	11.2 mm x 17.0 mm	
Weight	0.21 oz	6.0 gm	
T - TEDS Capable of Digital Memory and Communication Compliant with IEEE P1451.4			
TLA - TEDS LMS International - Free Format			
TLB - TEDS LMS International - Automotive Format			
TLC - TEDS LMS International - Aeronautical Format			
Temperature Range (Memory Access)	-10 to +250 °F	-23 to +121 °C	
Excitation Voltage	20 to 30 VDC	20 to 30 VDC	
Output Bias Voltage	7.5 to 13 VDC	7.5 to 13 VDC	
TLD - TEDS Capable of Digital Memory and Communication Compliant with IEEE 1451.4			
W - Water Resistant Cable			
Electrical Connector	Sealed Integral Cable	Sealed Integral Cable	
Electrical Connection Position	Side	Side	

Notes

[1] Typical.
[2] TEDS option adds 1.0 VDC to bias voltage.
[3] Zero-based, least-squares, straight line method.
[4] See PCB Declaration of Conformance PS023 for details.
[5] 250° F to 325° F data valid with HT option only.

Supplied Accessories

080A Adhesive Mounting Base (1)
080A109 Petro Wax (1)
081B05 Mounting Stud (10-32 to 10-32) (1)
ACS-1 NIST traceable frequency response (10 Hz to upper 5% point). ()
M081B05 Mounting Stud 10-32 to M6 X 0.75 (1)

Source: PCB Piezotronics Incorporation, 2012