ELECTROMAGNETIC FORCE GENERATION FOR DYNAMIC MODAL TESTING APPLICATIONS

NORLIDA BINTI JAMIL

Thesis submitted in fulfillment of the requirements
For the award of the degree of
Master of Engineering (Mechanical)

Faculty of Mechanical Engineering
UNIVERSITI MALAYSIA PAHANG

2015

ABSTRACT

Milling is one of the most common manufacturing processes for manufacturing sectors. However, high speed machining problems notably tool chatter in function of both spindle speed and depth of cut. Thus, many researchers found that to detect or reduce chatter is by determining its dynamic characteristics such as natural frequency, damping ratio, mode shapes and frequency response functions (FRFs). To predict the stability of the cutting tool system, modal testing using impact hammer is required to gain cutting tool’s dynamic properties and FRFs. However, this method is suited well for non-rotating tools, but cannot be used to identify the dynamic of a rotating spindle. Thus, a non-contacting Electromagnetic Actuator (EMA) was designed and guided by analytical and numerical method. The geometry was designed using magnetic circuit analysis (MCA) and generalized machined theory (GMT) before FE analysis was conducted using Magnetostatic-Ansys software. Next, impact hammer and EMA were used as a contacting and non-contacting exciter respectively at a conventional milling machine in order to determine the FRFs and dynamic properties of milling tool with amplitude and speed dependencies including comparing with static FRFs. Subsequently, dynamic characteristic and FRFs obtained using non-contacting EMA later used to establish Stability Lobe Diagram (SLD). The magnetostatic analysis result has shown the magnetic flux produced were stable and controllable. Besides, the study has shown a good agreement between impact hammer and EMA with 8.74 percent of percentage error. The error between EMA and impact hammer may have resulted from inconsistencies with impact hammer testing. It should be noted that the EMA applied a distributed load to the tool instead of a point load. Furthermore, the variability in frequency values from FEA is probably due to differences in the boundary conditions of the milling machine. The SLD also showed an improvement which up to 5 percent for depth of cut at lower spindle speed. Thus, EMA produced can determine dynamic properties yet for the purpose of chatter prediction. In conclusion, this research had successfully design and analyzes an EMA that can determine dynamic properties and SLD to increase MRR and production rate, by generating force applies for static and dynamic modal testing.

ABSTRAK

Pengisaran merupakan proses pembuatan yang umum dalam sektor pembuatan. Walau bagaimanpun, pemesinan berkelajuan tinggi menghadapi masalah utama iaitu gelatuk dimana berpunca dari kelajuan gelendong dan kedalaman suatu potongan. Oleh itu, ramai penyelidik mendapati bahawa untuk mengesan atau mengurangkan gelatuk adalah dengan menentukan ciri-ciri dinamik seperti frekuensi tabii, nisbah redaman, bentuk ragam dan fungsi sambutan frekuensi (FRFs). Untuk meramalkan kestabilan sistem alat pemotong, ujian ragaman menggunakan tukul hentaman diperlukan untuk mendapatkan sifat-sifat dinamik dan FRFs alat pemotong. Walau bagaimanapun, kaedah ini tidak sesuai untuk alat berputar, maka tidak boleh digunakan untuk mengenal pasti ciri dinamik gelendong yang berputar. Oleh itu, Penggerak Elektro Magnet (EMA) tidak bersentuh telah direka dan berpandukan kaedah analisis dan berangka. Geometrinya telah direka bentuk dengan menggunakan analisis litar magnet (MCA) dan teori mesin teritlak (GMT) sebelum analisis FE telah dijalankan menggunakan perisian Ansys-Magnet statik. Seterusnya, tukul hentaman dan EMA telah digunakan pada mesin pengisaran konvensional sebagai penguja bersentuh dan tidak bersentuh untuk menentukan FRFs dan sifat dinamik pada alatan kisar dengan bersandarkan amplitud dan kelajuan, kemudian dibandingkan dengan FRFs statik. Selepas itu, ciri-ciri dinamik dan FRFs yang diperoleh dengan menggunakan EMA tidak bersentuh kemudian digunakan untuk menghasilkan rajah kestabilan lobus (SLD). Hasil analisis magnetstatik telah menunjukkan fluks magnet yang dihasilkan adalah stabil dan terkawal. Selain itu, hasil siasatan menunjukkan bahawa pertalian antara tukul hentaman dan EMA adalah baik, dimana ralat peratusan adalah pada 8.74 peratus. Ralat yang kecil antara EMA dan tukul hentaman mungkin telah disebabkan oleh ketidakseragaman semasa ujian tukul hentaman dijalankan. Selain itu, ia harus diambil perhatian bahawa kenaan EMA kepada alat bersifat beban teragih dan bukannya beban titik. Tambahan pula, Kepelbagaian nilai frekuensi mungkin disebabkan oleh perbezaan dalam syarat-syarat sempadan mesin pengilangan. Lobus menunjukkan penambaikkan sehingga 5 peratus untuk kedalaman pemotongan pada kelajuan gelendong lebih rendah. Oleh itu, EMA yang dihasilkan boleh menentukan ciri-ciri dinamik lagi untuk tujuan ramalan gelatuk. Kesimpulannya, kajian ini telah berjaya mereka bentuk dan menganalisis sebuah EMA yang boleh memperoleh ciri-ciri dinamik dan SLD bagi meningkatkan MRR dan kadar pengeluaran, dengan menjana dan mengenakan daya bagi ujian mod statik dan dinamik.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

a_1	Failure probability life adjustment factor
a_2	Material life adjustment factor
a_3	Operation condition life adjustment factor
A_g	Area of gap
b	Limit of stability
b_{cr}	Critical depth of cut
b_{lim}	limited critical depth
B	Magnetic Field
c	Damping
dB	Decibel
E	Elastic modulus
f	Frequency
$f(t)$	Time delay between each tooth pass
Fm	Magneto motive force
$\mathcal{F}(\omega)$	Input force
G	Shear modulus
$G(s)$	Transfer function
h	Depth of cut
h_m	Mean chip thickness
H	Magnetic field intensity
$H(\omega)$	Transfer function
I	Current
k	Stiffness

Ks	Cutting stiffness
ℓ	Length of wire
l_g	Actuator gap
l_{gnom}	Nominal gap
L_{10a}	Adjusted basic rating life
L_{10}	Fatigue life that 90% of a group of bearings will endure
m	Mass
n	Integer number
N	Force
Q	Quality factor
R	Reluctance
t	Varying time
V	Voltage
X(ω)	Displacement response
y_p	Previous relative vibration
y	Current relative vibration
τ	Time delay between each tooth pass
Ω	Spindle speed
ω_n	Natural frequency
ξ	Damping ratio
Δf	Frequency width
μ	Poisson ratio
ρ	Density
ε	Phase shift

η_c	Number of coil
Φ	Magnetic flux

LIST OF ABBREVIATIONS

AMB	Active magnetic bearings
DAQ	Data acquisition
DDE	Delay differential equation
EMA	Electromechanical actuator
FFT	Fast Fourier transform
FEA	Finite element analysis
FRF	Frequency response functions
GMT	Generalized machine theory
HSC	High speed cutting
HSM	High Speed Machining
LDV	Laser Doppler vibrometry
MCA	Magnetic circuit analysis
MRR	Material removal rate
MDOF	Multi degree of freedom
RPM	Revolutions per minute
SD	Semi-discretization
SDoF	Single degree of freedom
SLD	Stability lobe diagram
TMD	Tuned mass dampers
TDS	Time domain simulation
ZOA	Zeroth order approximation

CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

High Speed Machining (HSM) is one of the many advanced manufacturing technologies that had been developed over the years. It has enabled the increase in efficiency, accuracy and quality of workpieces while at the same time decreasing costs and machining time (Schulz, H., 2003). There is no particular definition of high-speed machining because it has been defined differently by various authors. According to Longbottom (2006), the first definition of HSM was proposed by Carl Salomon in 1931. He assumed that HSM referred to machining that has cutting speed which is 5 –10 times higher than conventional machining. Coromant, S., (1999), Ekinovic, S. and Ekinovic, E., (2000) defined HSM differently as high cutting speed machining, high rotational speed machining, high feed machining, high speed and feed machining or high productive machining. Thus, it is apparent that HSM may be recognized as a relatively new production technology which enabled higher productivity, excellent surface finish and dimensional accuracy in manufacturing. The advances in machine tool performances (main spindle, feed drives, etc.), high-speed machining, particularly high-speed milling, became one of the factors which contributed towards cost-effective manufacturing processes. These enabled the manufacturing of products with high surface quality, economical alterations in machined surface and dimensional accuracy (Fallbohmer, P. et al., 2000; Becze, C.E. et al., 2000; Begic-Hajdarevic, D. et al., 2014).

However, high-speed machining can result in numerous dynamic problems. One of them was a form of self-excited vibration known as chatter. Chatter is a self-excited vibration that can occur when an overly large volume of material was removed for a particular spindle speed. A recent study by Palpandian P. et al. (2013) found that chatter was an undesirable phenomenon which can limit the productivity of the machine and reduce the material removal rate (MRR). It had also been reported that the occurrence of chatter can lead to a waste of materials and energy plus poor surface finish of the end products. The development of strategies to control the chatter has been done by a number of researchers and these will be described in the next chapter of this thesis. Stability lobe diagram (SLD) is an efficient tool which helps to select specific spindle speeds during production to avoid chatter in machine. Stability lobes are plotted against depth of cut versus spindle speed which shows a boundary between stable and unstable cutting regions. Figure 1.1 displays the SLD curve for stable and unstable zones.

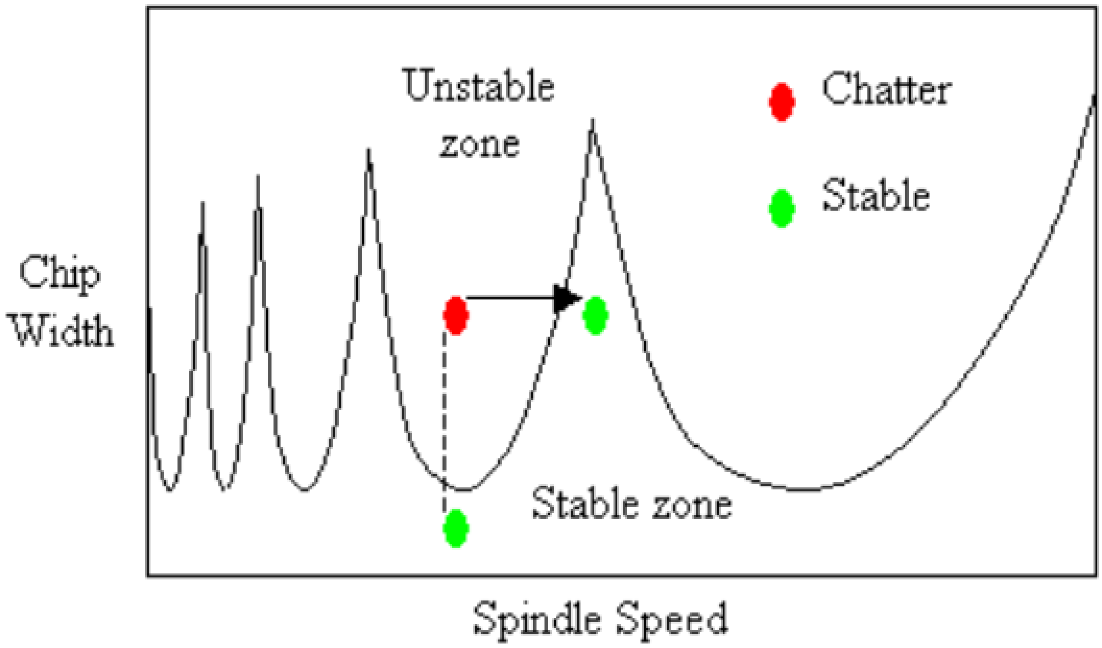

Figure 1.1: Example of a stability lobe diagram (SLD)

Source: Palpandian, P. et al.. (2013)

Tang, W.X. et al., (2009) reported the steps involved in the prediction of stability lobe diagram in their study. Initially, the dynamic characteristics and milling process parameters were obtained using modal testing. Then, the frequency response functions (FRFs) were determined by selecting the natural frequency and exciting frequency. Using FRF, stability milling limits were estimated and the stability lobe diagram was obtained.

The dynamic properties and FRFs of cutting tools were required for the use of modal testing. An impact hammer was traditionally used to excite the system at the tip of the tool and the response was measured with a co-located accelerometer shown in Figure1.2. However, this configuration had a number of disadvantages such as:

(i) The cutting edge of the tool can easily be damaged by the hammer strike.

(ii) On large machines, the test engineer must work within the machine itself which can pose a health and safety hazard.

(iii) The tool cannot be rotated during the test. The FRF during rotation could differ due to gyroscopic forces and bearing loads (De Lacalle. et al. 2009). Furthermore, some CNC machines automatically modified the tool drawbar force as a function of spindle speed which may influence the tool's FRF.

(iv) In practice, the mechanical interfaces in the system have led to some nonlinearity in the FRF. During machining, the tool load differed substantially from the forces induced by an impact hammer. Therefore, these nonlinearities cannot be considered.

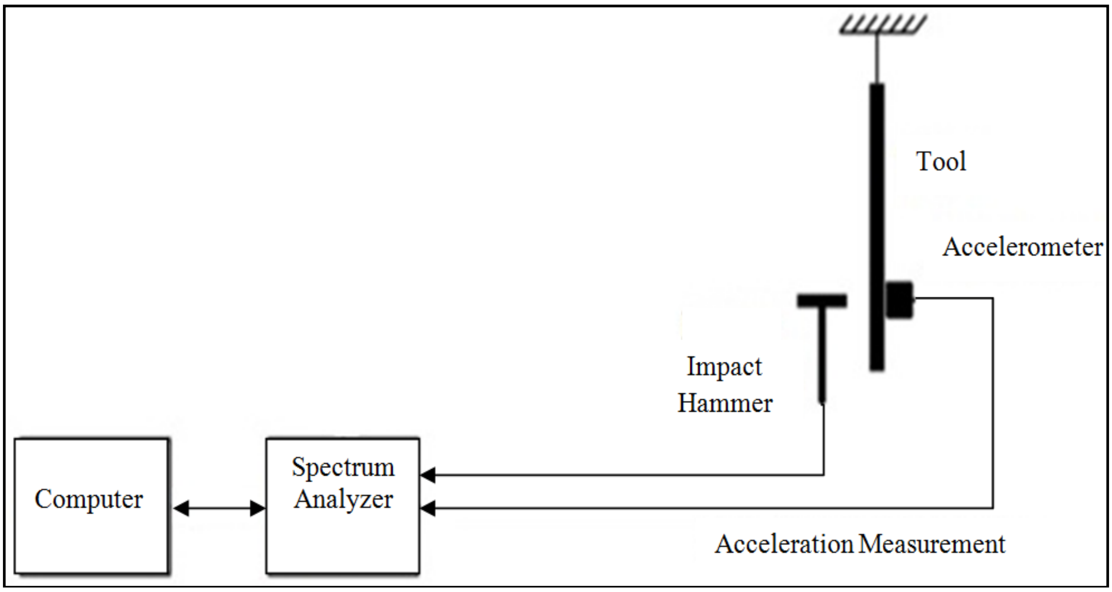

Figure 1.2: Experimental set-up for hammer excitation

Non-contact actuator offers advantages in terms of easiness to use, reduced test time, quick and easy setup as well as removal (Davies, M. et al., 2002). In addition, it is also less expensive. Caulfield, F.D. (2002) proposed that the force exerted on the tool and the density of magnetic flux in the air gap must be maximized because the overall actuator size had to be minimized. Sodano, H.A. (2006) discovered that the eddies of current losses were proportional to the excitation frequency. Additionally, the excitation waveform required actuator mount and the displacement sensor mount has higher natural frequency than the tool specimen. These were due to the interruption of sensor measurement to the system frequency during measurement.

The non-contact excitation systems were developed by several researchers. Rantatalo, M. et al. (2006) and Tatar, K. et al. (2007) used laser Doppler vibrometer (LDV), an active magnetic bearing and capacitive sensor to measure the dynamic vibration of cutting with an optically smooth surface at different cutting speeds. The mass loading added stiffness, and multiple hitting in traditional impact hammer can be eliminated by introducing non-contact eddy current excitation method to preserve the structure mode shape from magnetic actuation. On the other hand, Caulfield, F.D. (2002) designed and demonstrated the electromechanical actuator (EMA) that can identify dynamic characteristics of the machine. The design was based on magnetic circuit analysis, generalised machine theory and finite element method to confirm the performance. With the same objective, Kiefer, A. J. (2004) extended the work by integrated the electromagnet with receptance coupling substructure to predict chatter. The electromagnet demonstrated easy and accurate dynamic characteristic of cutting tool or FRF and generated high force amplitude, high bandwidth and controllability force. Yusoff, A.R. et. al. (2008) considered the amplitude dependency of the tool FRF under static condition. To date, Cao, H.R. et al. (2013) presented an alternative approach using LVD to predict SLD of high-speed milling with the consideration of speed-varying spindle dynamic. Then, Matsubara, A. et al. (2014) introduced a magnetic loading device which was used to provide swept-sine-wave load. The spindle displacements were measured with eddy-current-type sensors. The frequency response functions (FRFs) were obtained from the measured load and displacement. Finally, Lu, X.D. et al. (2014) proposed a three degrees of freedom linear magnetic actuator that also increased the damping and static stiffness of flexible structure during machining.

However, in general, these past studies did not consider the amplitude dependency of the tool FRF under dynamic condition. By using a non-contacting electromagnet, the amplitude and speed dependencies can be investigated experimentally. In addition, the dynamic properties behaviors to the rotor systems such as cutting the tool should be considered in predicting stability lobe diagram. These were focused in this thesis.

1.2 PROBLEM STATEMENTS

Milling is one of the most common manufacturing processes for automotive, mold and die and aerospace components, but its productivity is limited by the onset of regenerative chatter. This is a form of unstable self-excited vibration that occurs when the volume of material removed was too large for a particular spindle speed. Chatter is undesirable because it results in premature tool wear, poor surface finish on the machined component and the possibility of serious damage to the machine itself.

Chatter stability of a milling process can be determined using well-established theory, provided that the frequency response of the flexible structure can be determined. In practice, this usually involves excitation of a stationary (non-rotating) milling tool with a modal hammer and measurement of the response of the tool with a co-located accelerometer. However, this measurement is not necessarily accurate due to the consideration of amplitude and speed dependency factors. There is anecdotal evidence that structural nonlinearity can have a significant effect on the chatter stability of some milling machines. This research described the practical application of this approach and discussed its amplitude and speed dependencies for current excitation during FRF measurement using electromagnetic actuator force generation.

1.3 PROJECT AIM AND OBJECTIVES

This project aims to develop non-contact electromagnetic actuators for measuring the frequency response of milling tools under dynamic condition. In order to achieve the above the goal, specific objectives are constructed as follow:

(i) To determine frequency response function and dynamic properties of cutting tool systems with amplitude and speed dependencies using EMA, including the comparison with static FRFs.

(ii) To design and analyze an electromagnetic actuator to generate force to excite milling tool using Generalized Machine Theory (GMT), Magnetic Circuit Analysis (MCA) and Finite Element Analysis (FEA).

(iii) To conduct static modal testing using an impact hammer where the experiment results obtained are then used for the verification with FEA in order to determine natural frequencies and mode shapes.

1.4 RESEARCH SCOPES

Electromagnetic actuator (EMA) can be properly designed by using magnetic circuit analysis (MCA) and generalized magnetic theory (GMT). The force targeted to be generated by EMA was 10 N from 1 A RMS power amplifier for maximum 2 kHz frequency. An initial design of EMA should precisely examine and analyze from Finite element analysis (FEA) simulation. The EMA system was then fabricated based on an optimum EMA design from FEA analysis. It consisted of the coil, core, mounting system and laser displacement sensor. In order to test the fabricated EMA, natural frequency was initially checked with rotor system i.e. cutting tool and compared with the traditional method of the impact hammer under static condition. Instead of the static condition, the cutting tool was tested under dynamic conditions with an amplitude dependency using EMA system. Finally, the current EMA was applied to predict and validate the stability lobe diagram of chatter behavior during dynamic conditions.

1.5 THESIS ORGANISATION

The organisation for the rest of thesis is as follows; Chapter 2 specifically prescribes a literature review on the topic of electromagnetic generations for dynamic modal testing applications. Methods to control chatter in machining are then reviewed. Several techniques for modal were also discussed. For exciters, the types and methods of static and dynamic modal testing are described.

Chapter 3 initially highlights on all the issues related to the electromagnetic actuator design. In this chapter, the basic theory of magnetic actuator design using Magnetic Circuit Analysis (MCA) and Generalized Machine Theory (GMT) are discussed. Next, modal testing using impact hammer and non-contacting electromagnetic actuator are presented. The experiment with a dummy tool with its dynamic properties is measured under static and dynamic condition.

The discussion for analysis result of magnetic flux obtained from finite element analysis (FEA) is presented in Chapter 4. The result shows the usefulness and efficiency of EMA in order to verify magnetic properties of the actuator before the fabrication process was made. The next focus is the experimental results of impact hammer testing under static condition. The finite element analysis is extended to compare the result. The considerations of different test settings as well as the problems encountered during the test performance were then studied and the results of the tests were presented and compared. Besides, this chapter also briefly discusses the causes and effects of different input of current and voltage applied and speed dependency. The results of all tests are presented in the forms of the FRFs and dynamic properties for amplitude and speed dependencies. Finally, the dynamic properties, natural frequencies and damping ratios obtained were used to create stability lobe diagram of chatter behavior during cutting.

In Chapter 5, the conclusions, research contribution and some general suggestions for future studies in this area were stated. The overall organization of the thesis structure is shown in Figure 1.3.

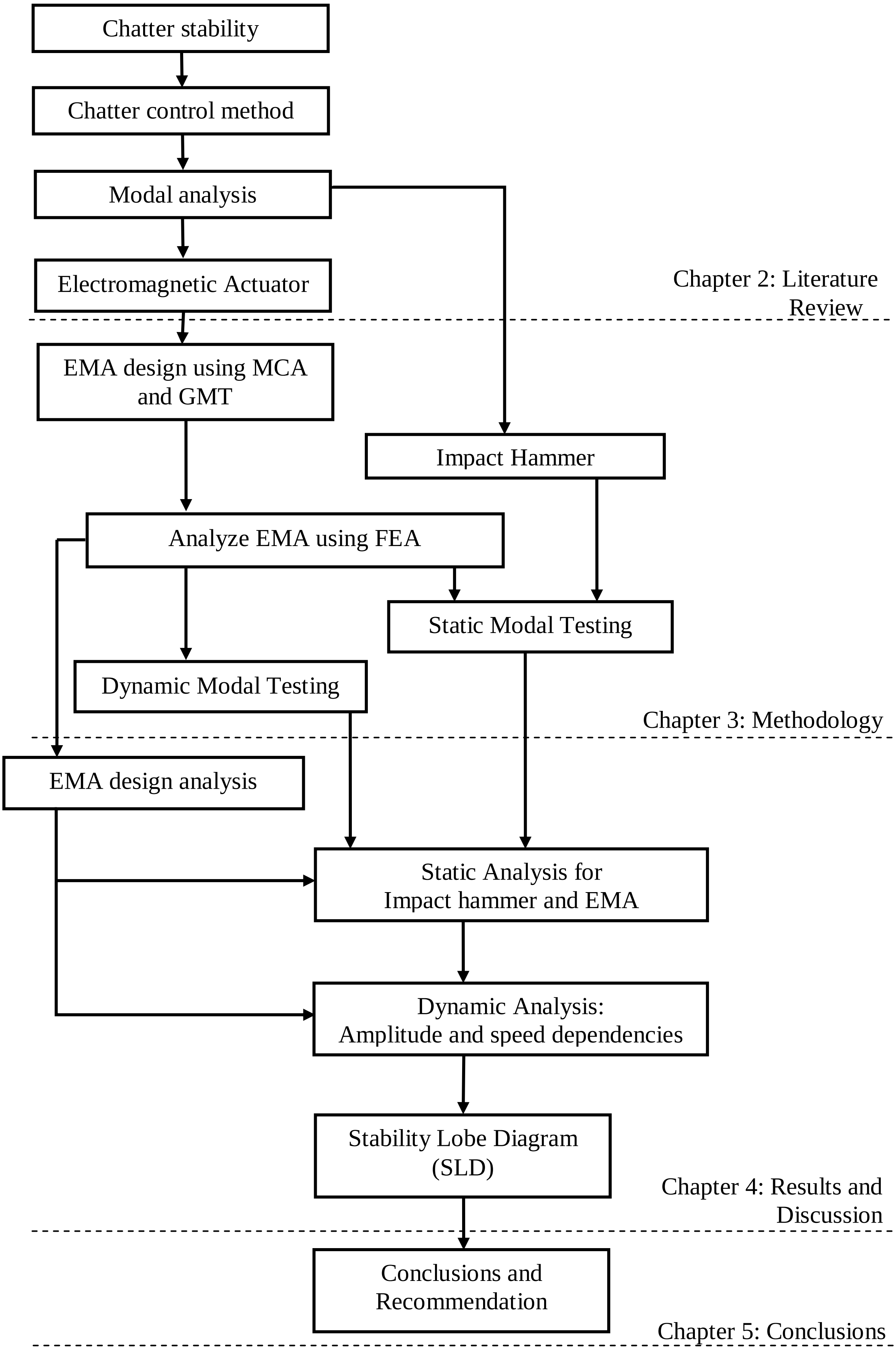

Figure 1.3: Overview of thesis

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

A review of previous research efforts related to machining process, chatter stability prediction and mitigation is presented in this chapter. This review starts with the definition and the types of machining process, followed by a brief explanation related to chatter, modal testing and the determination of frequency response functions (FRFs). Finally, at the end of this chapter, the overview of the electromagnetic actuator (EMA) testing analysis is described. A compilation of current literatures was done where the abstract can be found in Appendix A1.

2.2 MACHINING PROCESS

In the commercial applications of advanced materials, almost 90 percent of the materials estimated to be used in 2010 were metallic (Alcao, 2008). This indicated that despite the advances in composite materials, a rather great amount of attention was still focused on the metallic materials. The trend of choices of monolithic metallic components had enabled the manufacturing of products with a more efficient cost, weight and strength along with high dimensional accuracy even for complex parts. For example, for an aircraft made of 44 parts where 53 die sets were needed initially, the same section currently can be done with just six segments without dies by machining (Aronson, R.B., 1994). In addition, machining can also produce a smoother surface finish where a second hand finishing process is no longer needed which will save time and improve the quality. Hence, machining processes have been widely used in metal manufacturing rather than casting and forming. It has been found that milling is a more popular machining process than turning and grinding for the production of die cavities, slots, contours and profiles.

In the aerospace, automotive, mould-die and general manufacturing industries, there were great pressures in ensuring lower cost, greater productivity and improved quality in manufacturing processes in order to encourage economic growth. However, machining productivity using a high material removal rate is inhibited by the dynamic deflection of tool and workpiece systems which generated an unstable cutting force. This had produced a poor surface finish and resulted in not only a high rate of tool wear but it can even damage machine tools as a result of the regenerative effects, loss of contact effects and mode coupling effects. Regenerative chatter is perhaps the most common form of chatter (Tlusty, J., 2000) and it is discussed in the next section.

2.3 CHATTER

There are mainly three forms of self-excited chatters as shown in Figure 2.1. The first form is the velocity dependent chatter or self-excited chatter which occurred due to the dependence on the variation of force with the cutting speed. The second form is known as the regenerative chatter, which occurs when the unevenness of surface after being cut was due to the consequent variations in the cutting force during the cut. . The growing vibrations increased the cutting forces and produced a poor and wavy surface finish (Altintas, Y., 2012). The third form of chatter occurred due to mode coupling when forces acting in one direction on a machine tool structure cause movements in another direction and vice versa. This had resulted in simultaneous vibrations in two coupling directions. Physically, it was caused by a number of sources such as friction on the rake and clearance surfaces which was presented in Cook, N.H. (1959) and mathematically described by Wiercigroch, M. (1997).

Most of the chatters occurring in practical machining operations are regenerative chatters (Tobias, S.A., 1965) although other chatters are also common in some cases. These forms of chatters are interdependent and they can generate different types of chatter simultaneously. However, there is no unified model capable of explaining all of

CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

High Speed Machining (HSM) is one of the many advanced manufacturing technologies that had been developed over the years. It has enabled the increase in efficiency, accuracy and quality of workpieces while at the same time decreasing costs and machining time (Schulz, H., 2003). There is no particular definition of high-speed machining because it has been defined differently by various authors. According to Longbottom (2006), the first definition of HSM was proposed by Carl Salomon in 1931. He assumed that HSM referred to machining that has cutting speed which is 5 –10 times higher than conventional machining. Coromant, S., (1999), Ekinovic, S. and Ekinovic, E., (2000) defined HSM differently as high cutting speed machining, high rotational speed machining, high feed machining, high speed and feed machining or high productive machining. Thus, it is apparent that HSM may be recognized as a relatively new production technology which enabled higher productivity, excellent surface finish and dimensional accuracy in manufacturing. The advances in machine tool performances (main spindle, feed drives, etc.), high-speed machining, particularly high-speed milling, became one of the factors which contributed towards cost-effective manufacturing processes. These enabled the manufacturing of products with high surface quality, economical alterations in machined surface and dimensional accuracy (Fallbohmer, P. et al., 2000; Becze, C.E. et al., 2000; Begic-Hajdarevic, D. et al., 2014).

However, high-speed machining can result in numerous dynamic problems. One of them was a form of self-excited vibration known as chatter. Chatter is a self-excited vibration that can occur when an overly large volume of material was removed for a particular spindle speed. A recent study by Palpandian P. et al. (2013) found that chatter was an undesirable phenomenon which can limit the productivity of the machine and reduce the material removal rate (MRR). It had also been reported that the occurrence of chatter can lead to a waste of materials and energy plus poor surface finish of the end products. The development of strategies to control the chatter has been done by a number of researchers and these will be described in the next chapter of this thesis. Stability lobe diagram (SLD) is an efficient tool which helps to select specific spindle speeds during production to avoid chatter in machine. Stability lobes are plotted against depth of cut versus spindle speed which shows a boundary between stable and unstable cutting regions. Figure 1.1 displays the SLD curve for stable and unstable zones.

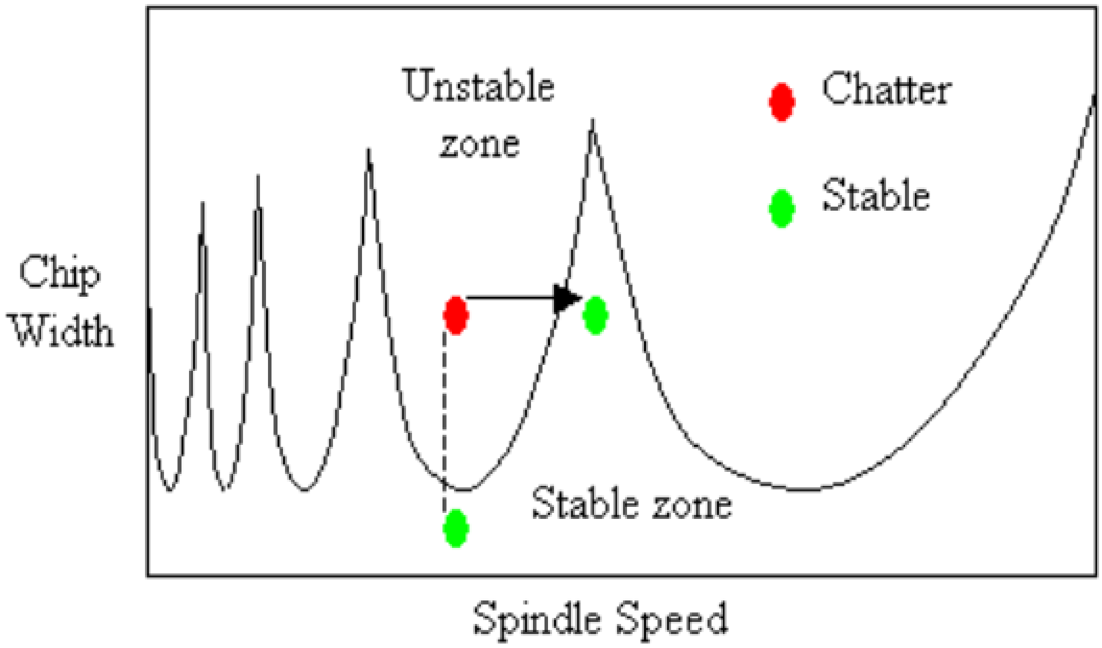

Figure 1.1: Example of a stability lobe diagram (SLD)

Source: Palpandian, P. et al.. (2013)

Tang, W.X. et al., (2009) reported the steps involved in the prediction of stability lobe diagram in their study. Initially, the dynamic characteristics and milling process parameters were obtained using modal testing. Then, the frequency response functions (FRFs) were determined by selecting the natural frequency and exciting frequency. Using FRF, stability milling limits were estimated and the stability lobe diagram was obtained.

The dynamic properties and FRFs of cutting tools were required for the use of modal testing. An impact hammer was traditionally used to excite the system at the tip of the tool and the response was measured with a co-located accelerometer shown in Figure1.2. However, this configuration had a number of disadvantages such as:

(i) The cutting edge of the tool can easily be damaged by the hammer strike.

(ii) On large machines, the test engineer must work within the machine itself which can pose a health and safety hazard.

(iii) The tool cannot be rotated during the test. The FRF during rotation could differ due to gyroscopic forces and bearing loads (De Lacalle. et al. 2009). Furthermore, some CNC machines automatically modified the tool drawbar force as a function of spindle speed which may influence the tool's FRF.

(iv) In practice, the mechanical interfaces in the system have led to some nonlinearity in the FRF. During machining, the tool load differed substantially from the forces induced by an impact hammer. Therefore, these nonlinearities cannot be considered.

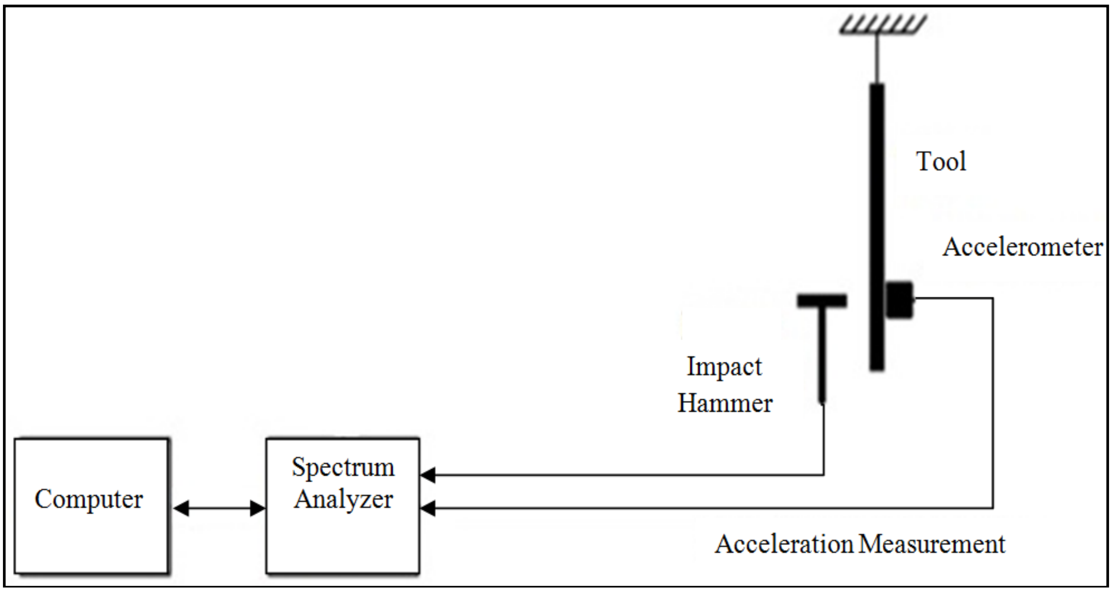

Figure 1.2: Experimental set-up for hammer excitation

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

In previous chapters, the introduction and literature of Electromagnetic Actuator (EMA) system were reviewed. This chapter starts by highlights the EMA system design analysis. The geometry of the actuator was designed using magnetic circuit analysis (MCA), generalized machine theory (GMT) and finite element analysis (FEA). Next, it continued with systematic procedures and details about experimental and finite element analysis (FEA) for structural evaluation processes of modal testing in milling machine. The experiments were conducted under static and dynamic condition. The experimental and FEA results were presented and discussed in next chapter.

3.2 ELECTROMAGNETIC ACTUATOR DESIGN

In this study, the objective for the actuator design was focused on creating the required 10 N force amplitudes. This had enabled accurate frequency response functions (FRFs) measurement for a representative range of machine tools. It was noted that the EMA was designed for use along with ferromagnetic tool materials as these can provide an ideal path for magnetic flux. The EMA was designed to produce controllable force profiles to tool blanks mounted in the tool holder of a conventional milling machine. Current one root mean square (rms) and voltage that was supplied to the core windings had created magnetic flux through the actuator core and across the air gap. When the tool was positioned in the gap, a magnetic attractive and reluctance force was developed in proportion to the core flux. This reluctance force provided controllable yet non-contacting excitation to achieve one kHz frequency range. Besides, this generation of prototype utilized a solid ferromagnetic core similar in performance characteristic to the first generation EMA prototype (Caulfield, F.D., 2002).

An E-frame core was selected because of its potential to have higher electromagnetic force compared to the C types that were previously used by other researchers (Sodano, H.A., 2006; Rantatalo, M., 2006; Tatar, K. et al., 2007). A single winding was wrapped around each layer of laminated electrical soft steel core. The initial design started with considering the E-frame electromagnet core with a rectangular cross-section as shown in Figure 3.1. A rectangular cross section was chosen because of the shape that can minimize the flux leakage while the straight section provided sufficient length for coil windings. In addition, Esterling, D. *et al*. (2003) also found that the criteria used to evaluate candidate core design were maximization of electromagnetic force on cutting tool, maximization of stable magnetic flux and minimization of overall actuator size.

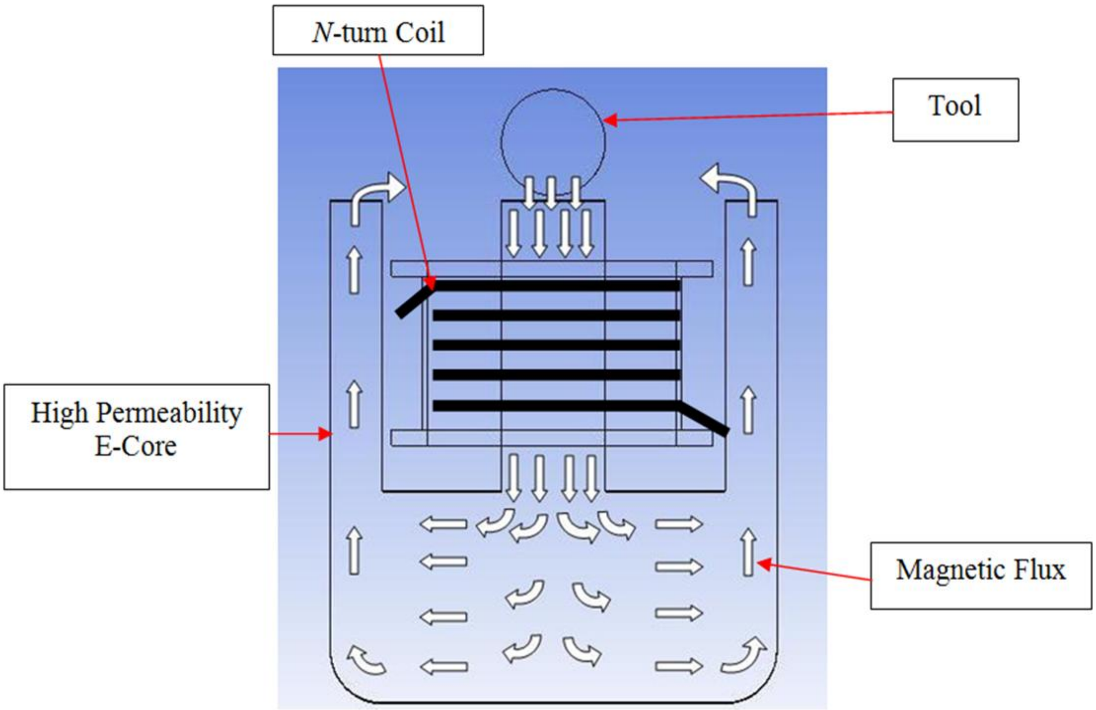

Figure 3.1: Electromagnetic Actuator Profile

In Figure 3.1, when a high current signal was applied to the coil, a controllable and stable magnetic flux was found in the core and air gap. Thus, when the cutting tool was placed on this air gap, the magnetic flux created a controllable force that can be used for FRF excitation (Caulfield, F.D., 2002). Based on the criteria in evaluating candidate core design stated earlier, the main consideration of EMA was the maximization of the magnetic flux in the air gap between the poles and cutting tool.

The core of an electromagnet must be constructed of a highly permeable material that was able to conduct magnetic flux. M-19 laminated electrical steel was an excellent choice for this application. The laminated electrical steel helped to minimize the magnetic skin effect known as eddy current losses in the core. Eddy currents were caused by time-varying magnetic fields in electrically conductive materials (Bae, J.S. et al., 2009). It has created heat and associated power losses in the core with focus on the outer surface of the conductor. According to the formula of average power loss per unit volume, it showed that eddy current power losses are proportional to excitation frequency, magnetic flux density and lastly square value of the lamination thickness (Slemon, G.R., 1966). Electrical steel has a relative magnetic permeability approximately four orders of magnitude higher than air. Hence, most of the magnetic flux produced in the coils was contained within the core. Furthermore, tool materials also have high relative permeability which was three to four orders of magnitude higher than air. Therefore, flux flowing through the core strongly favored a path through the tool. When it was inserted into the pole air gap, the air gap created the only significant reluctance to the magnetic flux in the actuator.

The target bandwidth for the EMA was therefore in range of 1000 Hz and the swept-sine excitation signal was predicted to sweep from 0 Hz to 1000 Hz. Other requirements for the EMA included manufacturing considerations, namely the ease and cost of manufacturing the actuator and the size of the unit. The EMA has several parts that required machining or forming. These included the actuator core, its mounting base and its cover. These components must fit together in a package that can be easily clamped into the workpiece holder of any standard milling machine. Design specifications for the EMA were summarized in Table 3.1.