FINITE ELEMENT ANALYSIS OF ELECTROMAGNET ACTUATOR FOR NON-CONTACT MODAL TESTING

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ABSTRACT

Chatter or self-excited vibration is always occurs during high speed machining operation. This phenomenon can reduce cutting tool life, poor surface finish on the machined component, and the possibility of serious damage to the machine itself. Before chatter stability can be predicted, modal testing is required to gain dynamic characteristic. This paper presents an analysis of initial design of EMA using Finite Element Analysis (FEA). This design of initial EMA will proper designed by using Magnetic Circuit Analysis (MCA) and Generalized Magnetic Theory (GMT). MCA is an analytical technique used to understand the magnetic flux characteristic of EMA, and GMT enabled predictions of the force capabilities based on the conservation of energy principle. The FEA software that will be used was the Finite Element Method for Magnetics (FEMM). Analysis result in the end can be displayed and plotted including flux path and density, and various field quantities. These methods predict that the actuator will produce sufficient force to create measurable deflection in cutting tools.

ABSTRAK

Getaran "Chatter" atau getaran mekanikal sentiasa berlaku semasa operasi mesin berkelajuan tinggi. Fenomena ini boleh mengurangkan mengurangkan hayat alat, kemasan permukaan yang lemah pada komponen yang dimesin, dan kemungkinan mesin mengalami kerosakan yang serius. Sebelum kestabilan getaran mekanikal ini boleh diramal, ujian mod diperlukan untuk mendapatkan ciri-ciri dinamiknya. Kertas kerja ini membentangkan analisis reka bentuk awal electromagnet penggerak (EMA) menggunakan Analisis Unsur Terhingga (FEA). Reka bentuk awal EMA ini telah direka dengan menggunakan Analisis Litar Magnetik (MCA) dan Teori Magnetik Biasa (GMT). MCA adalah teknik analisis yang digunakan untuk memahami ciri-ciri fluks magnet EMA, dan GMT membolehkan ramalan keupayaan daya yang berdasarkan prinsip pemuliharaan tenaga. Perisian FEA yang akan digunakan adalah Kaedah Unsur Terhingga bagi Magnetik (FEMM). Keputusan analisis akhirnya boleh dipaparkan dan diplotkan termasuk laluan fluks dan ketumpatan fluks dalam pelbagai cara. Kaedah-kaedah ini meramalkan bahawa penggerak akan menghasilkan kekuatan yang cukup untuk mewujudkan pesongan dalam alat pemotong yg boleh diukur .

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LIST OF SYMBOLS

a,b,h	Length, breadth and thickness of the plate (m)
a	Acceleration
m	Mass
k	Stiffness
t	Time
E	Elastic modulus (N/m^2)
f	Natural frequency of the plate (Hz)
ω_n	Natural frequency of the plat (rad/sec)
ρ	Density of the plate material (kg/m^3)
x,y,z	Cartesian coordinates
kg	Kilogram
N	Newton
μ	Poisson ratio

LIST OF ABBREVIATIONS

EMA	Electromagnet Actuator
MCA	Magnetic Circuit Analysis
GMT	Generalized Magnetic Theory
FEMM	Finite Element Method for Magnetic
3D	Three Dimensional
CAD	Computational Aided Design
FYP	Final Year Project
Al	Aluminium
ASTM	American Society for Testing and Materials
FEA	Finite Element Analysis
FEM	Finite Element Method
PM	Permanent Magnet
FRF	Frequency Response Function
MDOF	Multiple Degrees of Freedom
SDOF	Single Degree of Freedom
DAS	Data Acquisition System
IGS	Initial Graphics Exchanger Specification
HSM	High Speed Machining
CAE	Computer Aided Engineering

CHAPTER 1

INTRODUCTION AND GENERAL INFORMATION

1.1 PROJECT BACKGROUND

There is a lot of recent advancement in technologies and scientific studies lately. All the researcher are looking for the best way to solve any engineering related problem so that it will go to be smooth and clear process it what really matters nowadays. Engineering problems that are very crucial nowadays are malfunction of structure that contributed to the collapse or damage of structure. Regarding structure analysis or component analysis, modal analysis is the best way to conduct structural analysis as initial study before optimisation or further work will be done. Modal testing conventionally done by using Impact Hammer Modal Testing and Shaker Modal Testing which is in the category that require contacts between test devices and the material or part that been tested. However these contact modal testing sure has it flaws when it comes to area which need it to be tested on rotating object especially on High Speed Machining (HSM). The finite element analysis is a numerical technique for finding approximate solutions of partial differential equations (PDE) as well as for integral equations (Dr. Nagaraju, 2010). Based on design drawings, the dynamic characteristics of the electromagnet actuator for non-contact modal testing are studied using finite element analysis and ambient vibration measurements. Thus, a set of data is selected based on sensitivity analysis and optimization theory. This analysis can reflect the dynamic characteristics of the non-contact modal testing better, and it can be used to predict the dynamic response under complex external forces. It is also helpful for further damage identification and health condition monitoring.

1.2 PROBLEM STATEMENT

Since the industrial revolutionary there are lots of new machines were created to meet human needs in their daily activities and also the need of the development of the industrial activities. Since then, there are also lots of new materials used for the latest machines. The usages of the new machines bring the daily activities alive with the times.

However in the past days, the creations of these new machines were not going through modal analysis in order to observe its natural (modal) frequencies, modal masses, modal damping ratios and mode shapes of the machines and the test was not implemented since conventional modal testing required the test material to be contacted. Since the machines have its own movements such as rotation and others, thus conventional method is out of the list. Therefore this study proposed the need to come out with a non-contact modal testing procedure so that the same reliable result can be obtained without having any contact.

One of the best ways to implement this test is by using electromagnetic actuator. By using electromagnetic actuator, it can excite and come out with excitation force that will be picking up a capacitive displacement sensor on the other side. The subsequent process will be the same as a conventional method. The dynamic signal analyzer will analyze the data and it can be view and read in the computer.

1.3 PROJECT'S OBJECTIVE

The main objective towards the end of this study is:

1.3.1 To study the dynamic properties and behaviour of the electromagnet actuator for non-contact modal testing.

1.4 PROJECT SCOPES

This project is focusing on the dynamic properties and behaviour of electromagnet actuator for non-contact modal testing by using Finite Element Analysis (FEA) and modelling in Solidwork. This focus area is done based on the following aspects:

1.4.1 Design and draw electromagnet actuator for non-contact modal testing by using Solidwork.

1.4.2 Need to come out with previous research with experimental data or result

1.4.3 Use FEA-ANSYS for the analysis dynamic and mechanical properties

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

In this chapter, preliminary study that emphasizing high speed milling machine and chatter phenomenon and also structure analysis using modal analysis and numerical method like finite element analysis (FEA) used in solving engineering problems especially in magnetostatic problems and vibration concept will be this project main concern. FEA can be used in order to simulate what is really happening in the real experimental test since implementing the real test would consume a lot of money and might expose to greater problems if someone did not initiate this project with simulations first therefore this project shall start with FEA first. This chapter will highlight elements that involve in implementing this project and it's prioritized.

2.2 HIGH SPEED MACHINING

High Speed Machining (HSM) is one of the modern technologies, which in comparison with conventional cutting methods that enables to increase its efficiency, accuracy and quality of workpieces and at the same time to decrease costs and machining time (Pasko, R.). A major influence on the results of the machining process is caused by relative vibrations between workpiece and tool, which arise during the operation (U. Heisel, 1999). There are few elements which contribute to the occurance of the excitations such as the excitations of the imbalance, excitation of vibration cause by the machining process and excitation of vibration for accelerations movements (U. Heisel, 1999)

2.2.1 Background

Milling is the process of machining flat, curved, or irregular surfaces by feeding the workpiece against a rotating cutter containing a number of cutting edges (J.W. Sutherland, 1999). The usual Mill consists basically of a motor driven spindle, which mounts and revolves the milling cutter, and a reciprocating adjustable worktable, which mounts and feeds the workpiece. Milling machines are often classed in two basic forms, horizontal and vertical, which refer to the orientation of the main spindle. Both types range in size from small, bench-mounted devices to room-sized machines. Unlike a drill press, this holds the workpiece stationary as the drill moves axially to penetrate the material, milling machines also move the workpiece radially against the rotating milling cutter, which cuts on its sides as well as its tip. Workpiece and cutter movement are specifically controlled to less than 0.025 mm.

Milling machines also can be classified into several types such as that milling machine that may be manually operated, mechanically automated, or digitally automated via computer numerical control (CNC). Milling machines are able to perform several types of operations no matter it is simple or complex such as keyway cutting, drilling or even contouring. Cutting fluid is often pumped to the cutting area to cool and lubricate the cut.

Maximizing productivity is one of the most important objectives in the industry. As for milling processes, there are certain criteria that contribute to maximizing the material removal rate. The possible criteria were by increasing the spindle speed, increase the cutting depth and increase the feed rate. The enhancements of milling machine technology have contributed to the existence of machines with spindle speeds exceeding even 40,000 rpm.

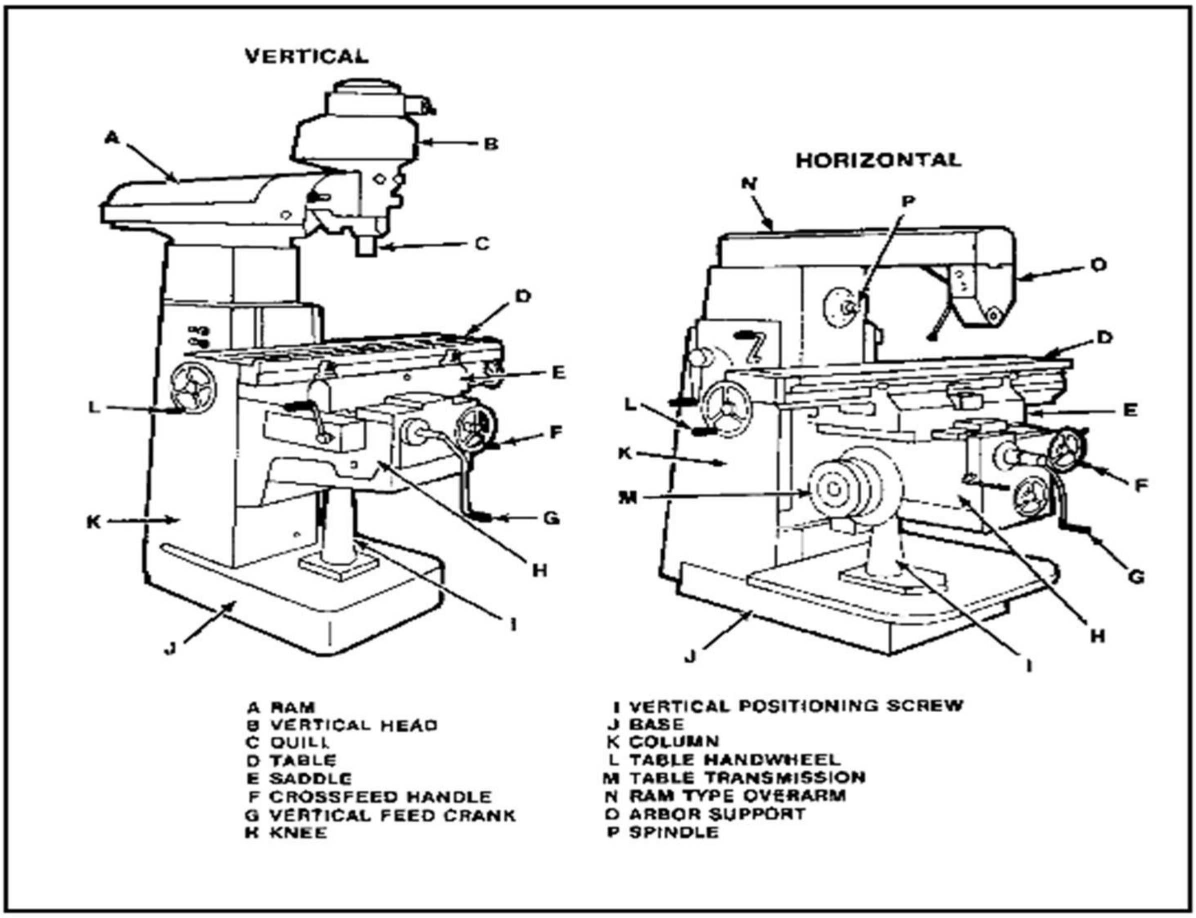

Figure 2.1: Milling Machine

Source: American Machine Tools Co (2002)

2.2.2 Advantage of HSM

One of the main advantages of HSM is it make it possible for the manufactures a practical and cost effective way to produce parts that cannot be easily produced by using standard machining processes (Caulfield, 2002). HSM ensures high metal removal rates, boost productivity, improve surface finish and eliminates the need of coolant (Pasko, R). It is also allow manufacturing lead time to reduce from months to days (Caulfield, 2002). Besides that, HSM also contribute to the reduced of the bur formation, better chip disposal and possibility of higher stability in cutting due to stability lobes against chatter vibration (Herbert Schulz, 1992).

2.3 CHATTER VIBRATION IN CUTTING

2.3.1 Background

Chatter can be defined as the vibrations that arise during the existence of relative movements between cutting tool and the workpiece. It is belong to the class of self-excited vibrations, which will definitely gives bad influence on surface finish, dimensional accuracy of the workpiece, tool life or even machine life (Ivana Kovacic, 1998). Several studies have been conducted on various mechanisms and characteristics of chatter. Cutting process with feed that has varies is one of the principals of the arising chatter vibrations. As in figure 2.3 below, chatter produced when the tool tips have contact with the workpiece which producing chips.

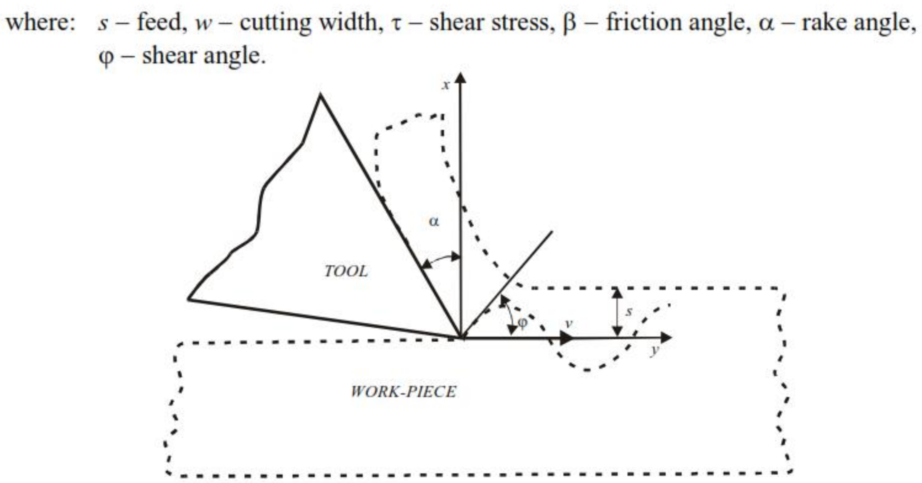

Figure 2.2: Cutting process with continuous chip formation

Source: Ivana Kovacic, 1998

2.4 VIBRATION ANALYSIS

Vibration can be most simply defined as a mechanical oscillatory motion. It is a movement first in one direction and then back again in the opposite direction. For instance, by a swinging pendulum, by the prongs of a tuning fork that has been struck, or by the string of a musical instrument that has been plucked. Random vibrations are exhibited by the molecules in matter. Any simple vibration is described by three factors which is its amplitude or size, its frequency or rate of oscillation and the phase or timing of the oscillations relative to some fixed time.

2.4.1 Types of Vibrations

1. Free vibration occurs when a mechanical system is set off with an initial input and then allowed to vibrate freely. Examples of this type of vibration are pulling a child back on a swing and then letting go or hitting a tuning fork and letting it ring. The mechanical system will then vibrate at one or more of its natural frequency and damp down to zero.

2. Forced vibration is when an alternating force or action is given to a mechanical system. Examples of this type of vibration include transportation vibration caused by its engine, its springs or road and also other external factors. Besides that, the vibration of a building during an earthquake one of the forced vibration example. In forced vibration, the frequency of the vibration is the frequency of the force or motion applied, with order of magnitude being dependent on the actual mechanical system.

2.4.2 Vibration Analysis Method

Vibration analysis method is a very useful method in order to perform the following analysis:

- Evaluating current machine condition
- Diagnosing faults associated with operational machines
- Monitoring and trending the overall condition of machines over time.

A complete vibration analysis would consist of three elements which is absolute vibration measurements, bearing condition measurements and FFT frequency analysis. The initial measurements, absolute vibration measurements, are an important indicator of the current state of a machine. They can be measured quickly and easily and have been successfully used for decades for the evaluation of overall machine condition (In-Plant Services Inc)

2.5 STRUCTURE ANALYSIS

2.5.1 Modal Analysis

Modal analysis is defined as the study of the dynamic characteristics of a mechanical structure. This application note emphasizes experimental modal techniques, specifically the method known as frequency response function testing. Other areas are treated in a general sense to introduce their elementary concepts and relationships to one another (Agilent Technologies)

Although modal techniques are mathematical in nature, the discussion is inclined toward practical application. Theory is presented as needed to enhance the logical development of ideas (Agilent Technologies). Even though it's quite complicated to explain modal testing, in easy way it could be characterize in involving three basic steps and essential:

- Exciting the dynamics of the structure
- Measuring the excitation and structural response of this excitation
- Analyzing the response to estimate modal characteristics of the future

Ideally, the excitation source should input a wide frequency range of energy to the structure, usually in the form of a swept sine or impulse function. The excitation source is normally an electrodynamics shaker or a modally tuned impact hammer. Modal responses are usually measured as accelerations or displacements at various points on the structure. These responses are commonly measured using optical, capacitive or eddy current displacement transducers or piezoelectric accelerometers.

Data analysis requires data acquisition and signal processing of sufficient bandwidth. Modal analysis can be performed using custom software programs or commercial analyzers specifically designed for testing. These units typically perform Fast Fourier Transforms (FFT) analyses and display system responses in the frequency domain.

2.5.1.1 Impact Hammer Modal Testing

The equipment required to conduct experimental impact hammer test includes a modally tuned impact hammer, a vibration measurement device, and a two-channel analyzer or data acquisition system. An impact hammer is a specialized piece of modal testing equipment used to excite a structure by emulating an impulse forcing function. A force sensor is attached to the tip of the hammer to provide the force measurement needed for analysis. A pictorial representation of an impact hammer test is shown in figure.

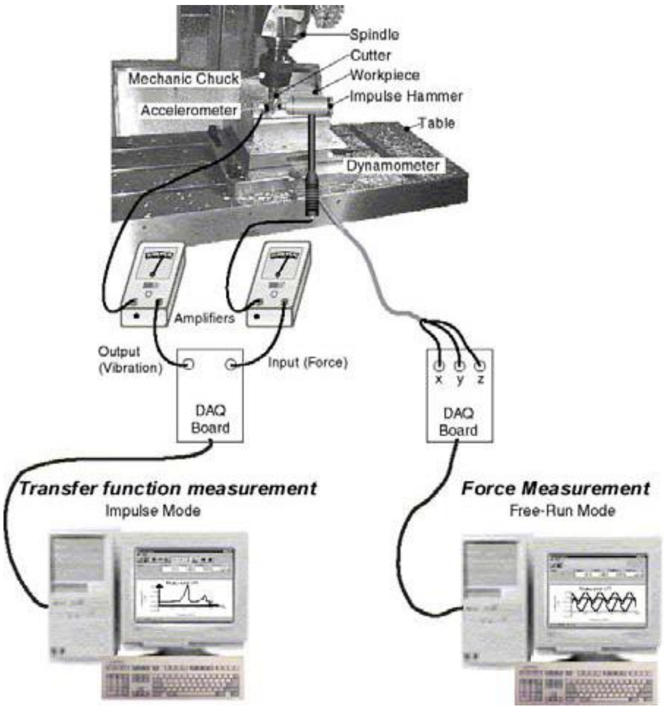

Figure 2.3: Impact Hammer Modal Testing

Source: Manufacturing Automation Lab Inc (1999)

Theoretically, an impulse input provides infinite amplitude over infinitesimal time duration, exciting all frequencies in the structure with constant amplitude. Basically, the hammer will be in contact with the structure for a finite amount of time and will impart a finite force. Considerable skill and technical resources are required to properly perform an impact hammer test. The impact must be ‘clean’ to produce the required broadband excitation. That is, it must be of very short duration and multiple knocks or bounces must be avoided. Higher frequency excitation suffers as the pulse width or time of contact turn out to be longer. Skill is also necessary to ensure consistent force input. Few machinists or production engineers possess the experience or expertise to make impact hammer testing practical in the machine shop environment (Caulfield, 2002).

2.5.1.2 Shaker Modal Testing

Even though the impact hammer is restricted to impulse force profiles, a number of other inputs are suitable for modal testing. These forcing functions can be produced by a signal generator or analyzer with appropriate output capability and amplified to power an electromagnetic or electro hydraulic shaker. Excitation signals commonly used in modal testing include:

- Stepped or swept sinusoids
- Random
- Impulsive

Stepped and swept sine excitations are similar. A sinusoidal force is applied starting at the lowest frequency of the range of interest and increased throughout the range. The stepped sine excitation, as the name implies is applied in discrete steps with enough resolution to yield meaningful Frequency Response Function (FRF) results. The swept sine excitation is increased continually through the frequency range. The suitability of the sweep rate can be tested by comparing measurements taken while sweeping up through the frequency range and then again while sweeping down through the range. One drawback to using shakers on light structures is the addition of mass, which may modify the modal characteristics. The frequency response measured will not reflect the true system dynamics in this case. This could be a significant limitation to the application of shaker testing on machine tools. Shaker tests typically require more sophisticated and expensive equipment such as signal generators, power amplifiers, and shakers rather than hammer impact tests (Caulfield, 2002).

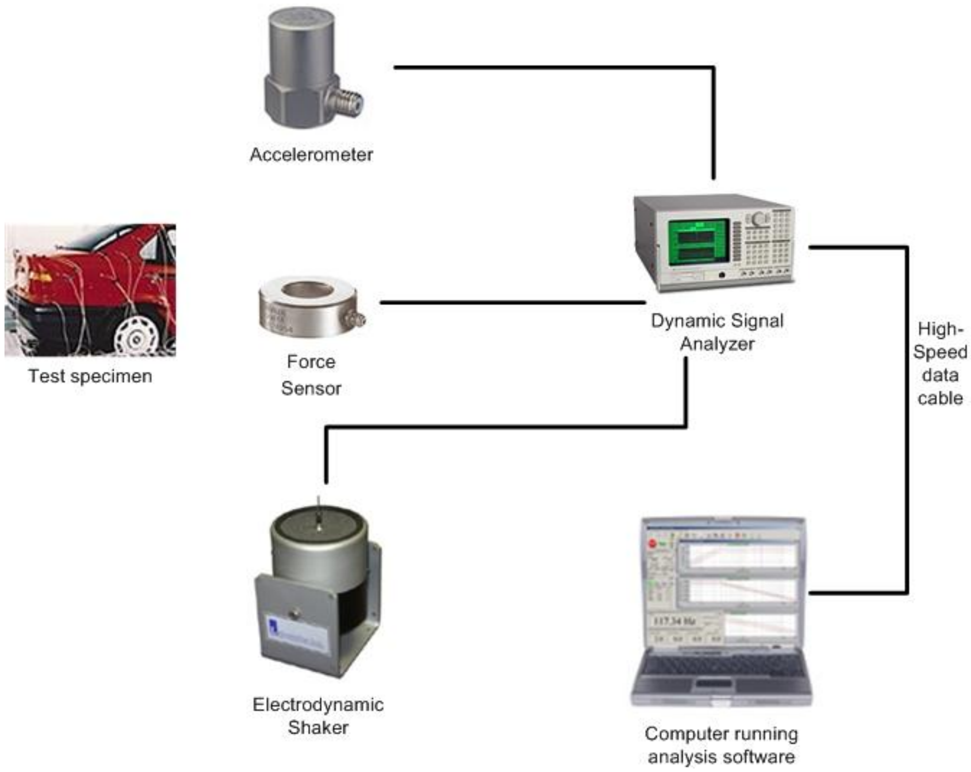

Figure 2.4: Shaker Modal Testing
Source: Jacek F. Gieras (2005)

The proficiency required to conduct shaker tests is maybe less than that required for impact hammer tests, but experience is required to set up the tests correctly. Tests can be time-consuming to set up, might be as much as an hour or even more and that will makes this method unfit for use in a production environment.

2.5.1.3 Non-contact Modal Testing

In the production environment, where chatter prediction is crucial, there is infrequently an opportunity to properly set up and perform modal tests without creating significant machine downtime. The impact of such tests on productivity is particularly severe for procedures that must be performed every time a tool is changed. Both the shaker and impact hammer approaches to modal testing are inconvenient to use on the shop floor. Not only do they require time to properly set up and execute, they also require considerable skill and experience to conduct. A more straightforward method is needed in order for chatter prediction to be widely practiced (Caulfield, 2002)

2.5.1.4 Electromagnet Actuator

Electromagnet actuator has been defined as the connecting links between information processing systems components of a controlling system and a technical or non-technical process (H. Janocha, 1992). From this observation towards this actuator working characteristics, it shows that the actuators are the technical elements which can adjust and control such as the flow of the energy. The imput might be just less power electrical signal but the output shall be torque for motors or thrust for translational movements.

In order to generate mechanical energy by using electromagnet actuator, a force must be produced by a magnetic field. The forces can be observed such as the current flow through conductors which exposed to magnetic field like Lorenz force as an example. The other type of forces also could be generated just simply by varying the reluctivity of the magnetic circuit along with its path of movement which are called reluctance forces. In order to design this actuator, both principles shall be applied on. Magnetic field for Lorenz force could be excited by using a permanent magnet material or by using windings. Windings are a form of various coils (E. Hering, 1999). However, normally both Lorenz and reluctance force effects are superposed. Therefore it leads this study towards one really important step which is determination of the change of the active air gap along the relative movement of the rotor and stator geometry. It is really important since in this study it is crucial to calculate the accurate force that will be produced later. However, the complicated geometries such as EMA model in this study require advance numerical methods to determine the air gap forces accurately. Figure 2.6 below show one of the EMA model design by Caulfield which possess nominal air gaps and the air gap was calculated in order to solve numerical problems.

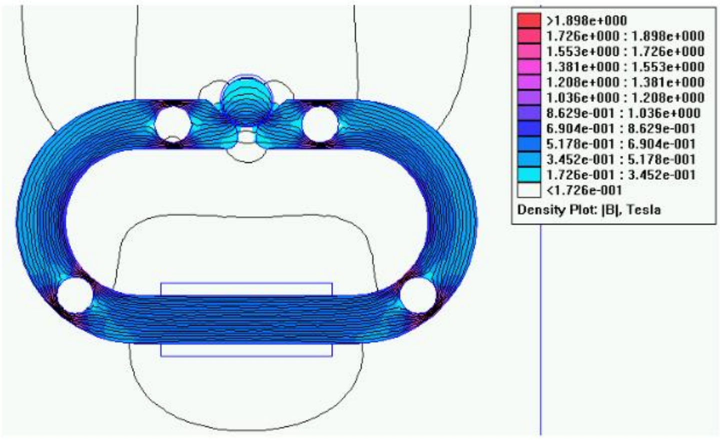

Figure 2.5: Flux analysis results of the EMA

Source: Caulfield, 2002

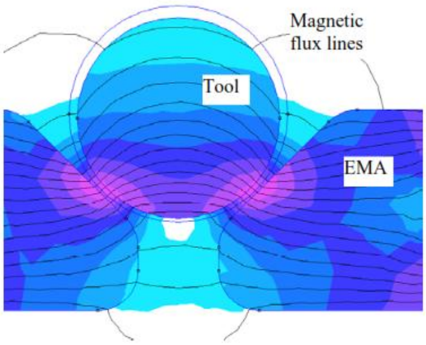

Figure 2.6: Magnetic flux in the air gaps

Source: Caulfield, 2002

Figure 2.7 above show close up of the EMA and the cutting tool which has close nominal gaps and its shows the magnetic flux line flow through from EMA to the cutting tool and flow back the other side of EMA.

2.5.1.5 Natural Frequency

Natural frequency is the frequency at which a structure naturally vibrates once it has been put into motion. The natural frequency is the frequency at which the system will oscillate without being tempered by external force. By considering the oscillation of a pendulum, the gravitational force is considered to be an inherent part of the system (S.