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SPINDLE SPEED MODULATION FOR CHATTER SUPPRESSION IN MACHINING PROCESS

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ABSTRACT

In manufacturing industry, productivity rate and profit is crucial. Higher productivity rate means the product can be released fast, with good quality. Unfortunately to increase the productivity, manufacturer have to face a big challenge which is chatter. Chatter is a wavy marks on a product surface finish that occur when self—excited vibration develop during the process, results in bad surface finish and unpleasant sound. The objective of this study is to analyse and supress chatter by modulating the spindle speed in machining process and to analyse the cutting condition during normal and spindle speed variation method. Though many research has been done using accelerometer sensor to detect the vibrations, this project make a full use of acoustic sensor to achieve the same goals. This project also involve the development of a PID controller to give on-line feedback to the machine based on data fed by the sensor. Data from acoustic sensor is analysed in time and frequency domain. The result also comparing the surface roughness of all cutting condition. This project succeed in improving the surface roughness of the material up until 86.7% after spindle speed variation has been implemented and the objectives of this project has been achieve. On top of that, the overall project contribute to great improvement of productivity rate through higher Material Removal Rate (MRR).

ABSTRAK

Dalam industri pembuatan, kadar produktiviti dan keuntungan adalah penting. Kadar produktiviti yang lebih tinggi bermakna produk tersebut boleh dibebaskan segera, dengan kualiti yang baik. Malangnya untuk meningkatkan produktiviti, pengeluar telah menghadapi satu cabaran besar , iaitu 'chatter' . Chatter adalah tanda berombak pada kemasan permukaan produk yang berlaku apabila getaran sendiri berlaku semasa proses, menjadikan kemasan permukaan yang tidak baik dan bunyi yang tidak menyenangkan. Objektif kajian ini adalah untuk menganalisa dan menyekat 'Chatter' dengan modulasi kelajuan gelendong dalam proses pemesinan dan untuk menganalisia keadaan pemotongan semasa kaedah perubahan kelajuan normal dan gelendong. Walaupun banyak kajian telah dilakukan dengan menggunakan sensor pecutan untuk mengesan getaran, projek ini menggunakan sepenuhnya sensor akustik untuk mencapai matlamat yang sama. Projek ini juga melibatkan pembangunan pengawal PID untuk memberikan maklum balas dalam talian ke mesin berdasarkan data diberi oleh sensor. Data dari sensor akustik dianalisis dalam domain masa dan frekuensi. Hasilnya juga membandingkan kekasaran permukaan semua keadaan memotong. Projek ini berjaya dalam meningkatkan kekasaran permukaan bahan sehingga 86.7% selepas perubahan kelajuan gelendong telah dilaksanakan dan objektif projek ini telah dicapai. Selain itu, projek keseluruhan menyumbang kepada peningkatan yang besar daripada kadar produktiviti melalui Kadar Pembuangan bahan yang lebih tinggi (MRR).

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CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

Manufacturing industry has becomes one of the world's leading industry that assure a good return of money. Speaking of business, it is often related to the profit and reputation of the manufacturer. In parallel with it, the user, demands of a better quality of product, and faster manufacturing process. These demands unknowingly becomes feedback to the manufacturer to control their product so that it satisfied their customer. To achieve such things, mass production with high speed machining have to be considered to increase the production rate and also to reduce cost.

In pursuit of achieving high production rate, the pleasure very fast manufacturing process do not last long until a phenomenon, that being hate by every machinist occur. It is called machine vibration or chatter. One of infamous manufacturing process which is listed in machining category, milling process is not exempt from this situation.

Chatter occur when the machining process is unstable. High speed production and material removal rate (MRR) in machining could lead to self-excited vibration of the cutting tool and the workpiece, as written by *Budak and Altintaş (1998a)*. Now this phenomenon not just stop there but it could result in poor surface finish, which a type of surface finish that have a wavy patterns, a dimensional inaccuracy, chipping of cutter teeth, and may damage the work piece and the machining tool.

To control chatter, the indisputable technique is to find the parameter which is quick enough to increase the production rate ,with considerably high MRR, plus the product surface finish is good enough before the chatter starts to develop. In short, it is optimum. In the end, a set of parameter can be deduced as a guideline.

The research of chatter on the particular of parameter selections in machining to avoid the built-up of these undesired oscillation becomes focus after the early research, which the presence of negative damping that is believed as the only source of chatter (*Budak and Altintaş (1998a)*). *Walter Lindolfo Weingaertner (2003)* believed that to avoid chatter, the MRR is often reduce, abdicating the power and torque available on the spindle. Next, a method of spindle speed variation to control chatter is introduced. This method allow machinist to maintain or increase depth of cut without worry with the correct spindle speed and chatter is then kept under control (*Yilmaz, Al-Regib, and Ni (2002)*). Then, it follow by the analytical prediction of chatter.

In this research project, experiment is set up by collecting the data of particular MRR using an acoustic sensor to find the optimum spindle speed that give a positive result in high speed milling operation before chatter is develop.

1.2 PROBLEM STATEMENT

The main problem of the research is obviously the chatter or self-exited vibration that occurred between cutting tool and the workpiece which result in poor surface finish. As the problem develops, it leads to another problem that are increasing the rate of tool wear and damaging the workpiece. With conjunction of these problems and effects, manufacturer and machinist have to bear with the high cost of maintenance and repairing.

1.3 OBJECTIVES OF THE RESEARCH

The following are the objectives of the project:

i. To design and implement the spindle speed modulation and variation for chatter suppression in mini CNC machine,

ii. To analyse cutting conditions during,normal and spindle speed modulation in machining process

1.4 SCOPE OF THE RESEARCH

Scopes of this project is to detect the presence of chatter during high speed milling operation with acoustic sensor with sensitivity of 2.0mV/Pa. Experiment parameter is set to 0.1mm to 0.3 mm depth of cut, 2800 to 3000 mm/min feed rate and 3000 to 20000 rpm spindle speed based on the machine maximum capability. Data is recorded and analysed in time and frequency domain, by using DASYLab version 10 and MATLAB R2013a software respectively, as well as the observation on surface finish, surface roughness and produced sound.

1.5 FLOW CHART

The work sequence has been planned as shown in Figure 1.1 in order to achieve the objectives of this research. This flow chart act as a useful guideline to ensure the smoothness of carrying the experiment. The process involves in achieving notified objectives includes the literature study of the related topic, determining material, method and parameters, conducting experiment, analysis data and the discussion.

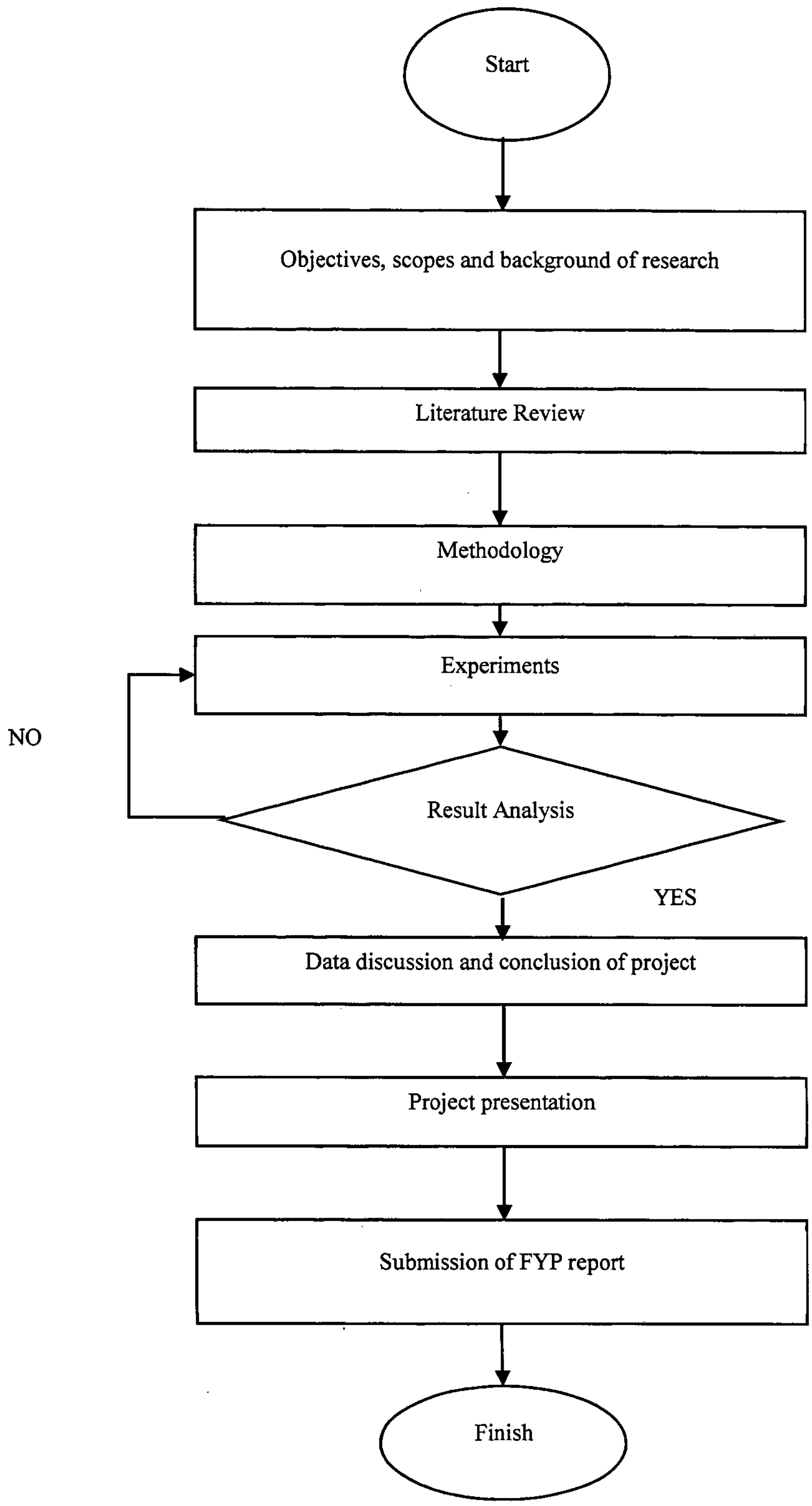


Figure 1.1: Project flowchart

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Manufacturing process plays a big role in the world various industries. As the world becomes more advance, people tend to build or invent gadget and parts. The science behind it continue to move rapidly and give major impact in the financial system of people.

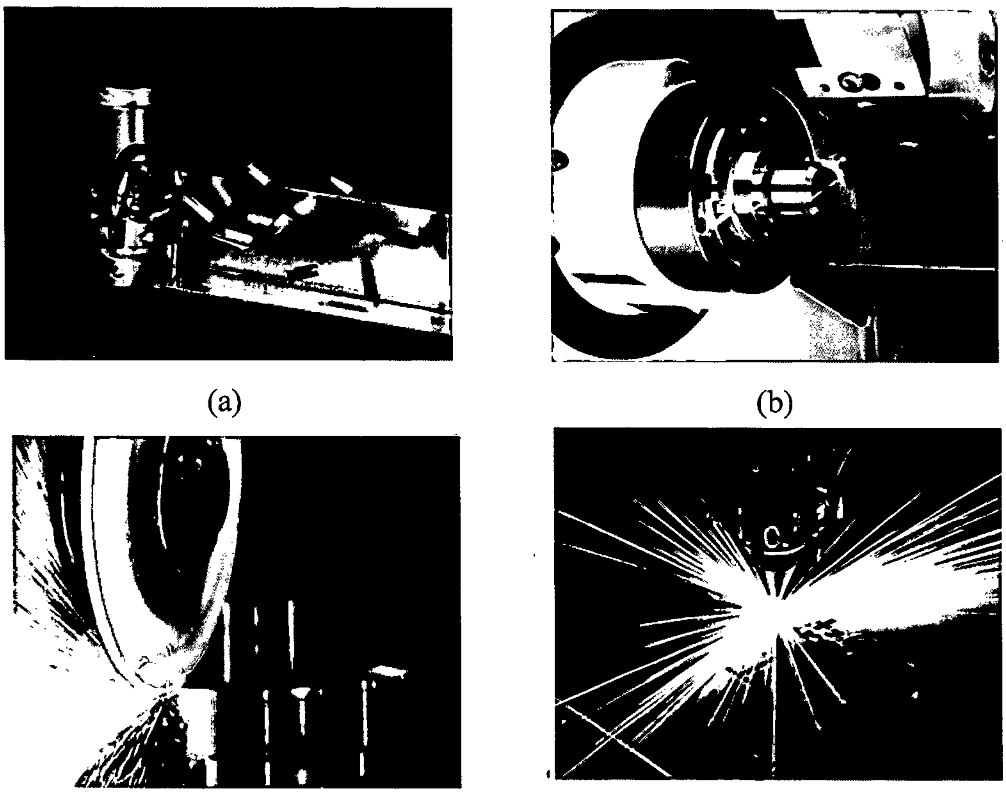
There are many types of manufacturing process available to form the desired shape of material. They are classified into five groups. In casting process, the material is given the desired shape and size of the product by melting it, poured into a cavity and allowing it to solidify. Machining is a removing the unwanted material from a given workpiece to create the required shape. Forming is made use of suitable force, pressure or stress like compression, tension, shear or their combination to cause a permanent deformation of the material. In powder metallurgy process, fine powdered materials are blended, pressed into the desired shape in a die 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 permanently, semi-permanent or temporary.

Manufacturing have a great relationship with business, where the manufacturer compete each other to produce better quality of products. To achieve such condition, a suitable types of process is required to match with the time constrain without neglecting the quality of the product such as the surface finish. In the meantime, manufacturer also have to consider the cost of manufacturing the product. Besides the cost of the material itself, manufacturer have to constantly monitor the quality and allocate funds for a research on the problem occur when they are involves in high speed machining.

2.2 MACHINING

After being formed into a specific shape and size, the parts will undergo further manufacturing process which is machining. In this process, the work piece are cut to create a detail profile using a specific cutting tool. This process is described a group of process that consist of the removal of material and modification of the surface of workpiece after it has been produce by various methods as stated by *Kalpakjian and Schmid (2010).*

In general machining consist of several major types of material removal process. Cutting, typically involving a single-point or multipoint cutting tools, each with clearly defined shape. Abrasive processes, such as grinding and advance machining process which utilizing electrical, chemical, laser, thermal, and hydrodynamic method to accomplish the task. Figure 2.1 shows the example of typical manufacturing process that commonly used in industry.



(a) (b) (c) (d)

Figure 2.1: Typical manufacturing process in industry. (a) Milling process, (b) Turning process, (c) Grinding process, (d) Laser cutting process.

Source: Wikipedia

2.3 HIGH SPEED MACHINING

High speed machining (HSM) refers to the speed of the cutting process takes place. In most cases, HSM always referred as high spindle speed. The truth about HSM is the material removal rate (MRR) which consist of the product of the feed rate, f, axial depth of cut, A_x and diameter of cutting tool, d , as shown in Equation 1.1. Any of these parameter can be combined to produce high rate of material removal which means it can accelerate the productivity. A research by Schultz and Moriwaki (1992) found that an optimum HSM could reduce time taken of the cutting process up to 50%.

$$MRR = A_x \times d \times f \quad (1.1)$$

Basic milling feed (feed per tooth) is the distance the workpiece advance in the time between engagements by the successive teeth. The machine feed rate is given Equation 1.2.

$$f = f_t * Z * n \quad (1.2)$$

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 speed is considerably less than the nominal feed per tooth for shallow cuts as shown in Figure 2.2. According to Schrader and Elshennawy (2000), when the depth of cut is at least equal to the radius of cutter, the two components of feed are equal. For end mill, depth of cut should not exceed half of the diameter of tool in steel, but in soften metals such as aluminium, it can be more.

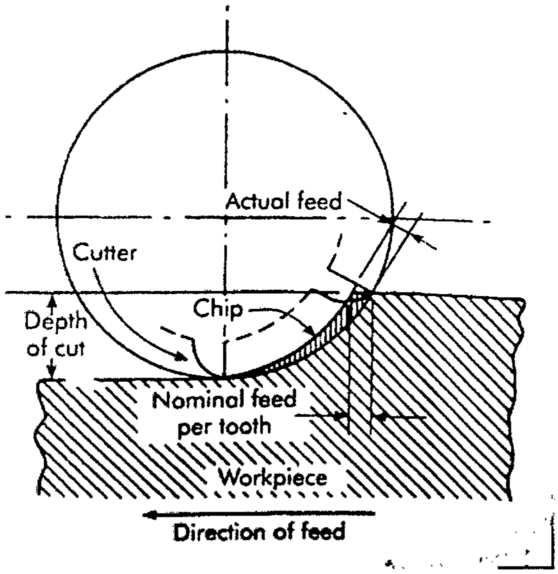


Figure 2.2: Actual feed vs. nominal feed for milling operation

Source: Schrader and Elshennawy (2000)

2.4 PID CONTROLLER

A proportional-Integral-derivative (PID) controller is a closed loop controller that continuously calculate error of the input variable with the desired set point. PID controller is widely used in industry in several of usage. In this type of controller, the constant value of K_p, K_i,and K_d plays a big role to measure the robustness of the controller. It does not have a specific value, which means, in different type of system might have different set of constant value. The constants form a summation algorithm as shown in Equation 1.3.

$$\mathrm{u}(t) = \mathrm{MV}(t) = K_p e(t) + K_i \int_0^t e(\tau)\, d\tau + K_d \frac{de(t)}{dt} \quad (1.3)$$

Where,

K_p: Proportional gain, a tuning parameter

K_i: Integral gain, a tuning parameter

K_d: Derivative gain, a tuning parameter

e: Error = SP - PV

SP: Set Point

PV: Process Variable

t: Time or instantaneous time (the present)

τ: Variable of integration; takes on values from time 0 to the present t.

2.5 FAST FOURIER TRANSFORM (FFT)

FFT is the technique to convert the signal from time domain into the frequency domain. The signal at detector, disability or on the display oscilloscope are usually shown in time domain. After transformation signal will shows how the amplitude varies with frequency. This view is often called 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 give the spread of frequencies in frequency domain *(Edward et al., 2007)*. Spike is made by adding sine waves of all different frequencies at one point while the spike at the other times are cancelled to gives zero signal.

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

2.6 CHATTER IN MACHINING

Machine vibration or chatter is a phenomenon that occurs due to the relative movement between workpiece and cutting tool. It is something that machinist hate since it results in waves on the machines surface. The effect of chatter usually appear in the typical machine process such as milling, turning and drilling.

Based on the research, chatter, that give effect to the surface finish may reduce the quality of the product and also reduce the process rate. In general, chatter leads to poor surface finish, increase rate of tool wear and reduce spindle lifetime. One of the reason behind this phenomenon is the surface regeneration, i.e., tools cuts a surface that was modulated by previous cut. Generally, conservative material removal rates, which cause reduce productivity are used to avoid chatter vibrations as stated by *Budak and Altintaş (1998b)*.

The Theory of regenerative machine tool chatter is based on the work of *Tobias and Fishwick (1958)* initially dedicated to the turning process . However, it has been adapted to milling by *Altintaş and Budak (1995)* which led to development of stability lobes theory. The theory is then use to construct stability lobe diagrams that help in selecting the spindle speed and axial depth cut. The diagrams present the stability boundaries, separating stable and unstable machining. Below boundaries, the process considered stable and above boundaries, it is unstable. In case of close to boundaries, rate of change of vibration of workpiece or tools is small (i.e. Exponential time constant is large). So, the identification of chatter might be not so clear. For instance, for process parameter that slightly above the boundaries, the operation terminated as chatter is developing (*Seguy et al. (2010)*). In case of non-linearity of parameter interaction in production setting, optimal speed difficult to find in many practical cases.

Another source of chatter vibration is the subtle shift between vibration of workpiece or tools and the tooth passing frequency. Phase shift leads to chatter frequency to go lower or higher than multiple of tooth passing frequency.

2.6.1 Chatter in Milling Process

One of the structural modes of the machine tool – workpiece system is the excited by cutting force initially during milling process. Due to structural vibrations, an oscillatory surface finish left by one of the tooth is removed by the succeeding oscillatory tooth. The resulting chips 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, under excessive cutting forces, chatter vibrations grow until the tools jumps out of the cut or break as in research of *Altintaş and Budak (1995)*.

That is why the major limiting factor in increasing the material removal rates of the machine tools is chatter vibration. Figure 2.3 shows the example of chatter marks when chatter occur in machining process.

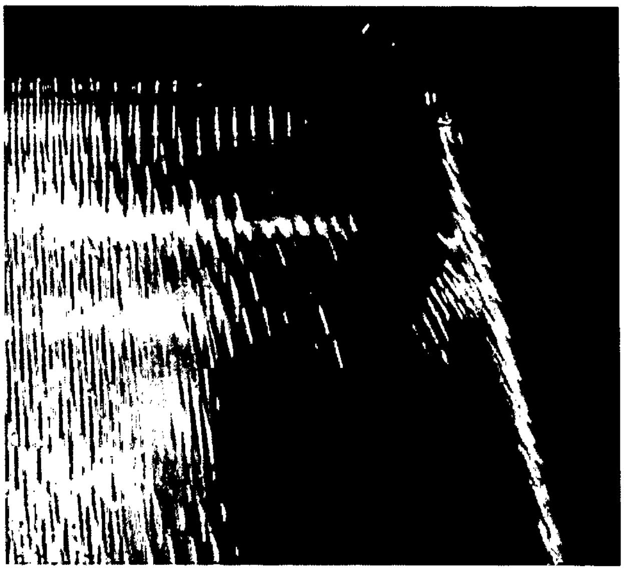


Figure 2.3: Wavy surface when chatter occur

Source: Google Image

2.6.2 Development of Chatter Research

Chatter as a regenerative phenomenon paper were published by *Tobias et al.*, in year 1958. Later, research presented the problem as a feedback loop, which clarify a lot of formulation by *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.

Later on, the method which enable working with several degree of freedom models is presented by *Altintas and Budak (1995)*. Analysis for the geometrical non-liniearities of the milling process obtain an approach to the solution by using a Fourier series development of the directional factors and solved the system by considering the zero order terms only.

Next three years, Budak and Altintaş (1998b) worked out the system by considering several terms of the Fourier development, which gives rise to solution very close to those obtained by using fundamental terms only .

Analytical methods that explicitly account for the interrupted nature of milling and have generated stability diagrams analogous to the classical 'lobes' have been proposed by researchers. The intermittent was captured by many harmonics in the Fourier series of the time carrying 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 process was used by *Davies et al. (2002)*), where the time in the cut is infinitesimal and the cutting process is modelled as an impact. An approximate expression was derived for the time delay form of an integral, time-periodic matrix differential equation, and use Floquet theory to determine stability boundaries (*Insperger and Stepan (2000)*).

The technique of semi-discretization was developed later *Insperger and Stepan (2004)*, while the similar results using temporal finite elements was obtain by *Bayly et al. (2003)*.

The multi-frequency resolution is also able to present accurately the flip instability phenomenon was showed (*Merdol and Altintas (2004)*). In specific research, just a few papers analysed the chatter in milling with the inclusion of the effect of helix angle. Without associated with the helix angle of 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 to simultaneous machining. This process can be further optimized by determining the best combination of the chip loads and spindle speeds with constrain chatter instability (*Olgac and Sipahi (2005)*).

2.7 CHATTER SUPPRESSION BY SPINDLE SPEED VARIATION

There are few possible ways to suppress chatter. It includes the Application of variable tool pitches. Other than that, the continuous spindle speed variation also an option which it can effectively be used in a wider spindle speed range, since the frequency and amplitude of spindle speed variation can be easily adjusted in CNC machines even during the machining process. In facts, this technique becomes focus of interest in 1970's.

Spindle speed variation method can serve two purposes, which to avoid machine-tool self-excited vibration associated with existing depth of cuts, and improvement of productivity through higher depth of cut as written by *Yilmaz, Al-Regib, and Ni (2002); Zatarain et al. (2008)* . He proposed the multi-level random spindle speed variation technique that will randomly change the spindle speed in fixed time interval. This type of spindle speed variation represent a stand-alone controller that generate continuous signal with amplitude range usually not exceeding of 40 % of nominal speed based on the spindle speed limitation.

Takamura et al. (1974) presented first simple model to study the stability of variable speed machining. Predicted a significant shift of the stability lobes to higher depth of cut, but the experimental test only show small improvements. *Sexton et al. (1977)* developed more realistic model. The research found some improvements in stability properties for low spindle speeds. The research conclude that the method of spindle speed variation (SSV) is shown to increase stability, in general, for single point cutting. However, the methodology used in the research is just only the numerical simulation. Next, *Sexton and Stone (1980)* showed that the presence of transient vibrations may drastically reduce these gains.

Research by *Jemielniak and Widota (1984)* found that the variation of the frequency of self-excited vibration is the main mechanism of the influence of the SSV on the stability of the system. The influence on the stability limit is exercise by the relative amplitude of SSV. The value of this amplitude can result in efficient suppression of chatter. He agree that one must find he root cause to a problem before solving it. As chatter develop with presence of self-excited vibration, the frequency of the self-excited vibration itself must be detected, then SSV suppression technique can be implemented.

At the beginning of the 1990s, the technique for automatic regulation or selection of a stable spindle speed was introduced by *Smith and Tlusty (1992)* and operated in recent years to produce monolithic Aluminium parts.

The effects of variable speed cutting was studied and it is found that sinusoidal wave is more suitable than other periodic function such as triangular wave and square wave in terms of both traceability by the spindle servo system and the performance in terms of vibration suppression and it is conclude that variable speed cutting using sinusoidal speed trajectory increase the stability of machining system against self-excited vibration over the wide range of nominal speed and machining system dynamics (*Lin, DeVor, and Kapoor (1990); Zatarain et al. (2008)*). However, other types of waves also can be used with different interest and accuracy.

Despite of this very powerful technique, the relation of nominal speed and dominant frequency must be considered when designing speed trajectory for a specific application. Analysis of data must include on how the frequency change with spindle speed and with other influence.

At high spindle speed machining, the optimum sinusoidal spindle speed variation (S^3V) amplitude ratio is very high and beyond the allowable range by available spindle-drive system as stated by *Al-Regib, Ni, and Lee (2003)*. Thus the feasible method is applying spindle speed selection method.

Smith and Tlusty (1992) described the basic theory of eliminating milling chatter by automatic spindle speed regulation. The system they proposed does not require any knowledge of the system dynamics, and selects a stable speed where chatter does not emerge. His research also acknowledged by *Bediaga et al. (2009).*

Delio, Tlusty, and Smith (1992) came out with a research of used of audio signal for chatter detection and control. They found that using an acoustic sensor such as microphone capable of detecting chatter arising from tool, workpiece, and machine flexibilities. One more advantage is it can collect chatter signal even in low-immersion cut. This paper gives a significant value as it provides a validation of the project, which is to detect chatter in low depth of cut.

To avoid chatter, the spindle speed have to be controlled as the MRR can be increase substantially. A technique was proposed to control machine spindle speed by means collecting the frequency data of the cutting process and feed them back to controller to adjust the spindle speed by *Bediaga et al. (2009).* He agree that the knowledge required for spindle speed variation method are the chatter frequency and spindle speed of the machine.

Later on, many research regarding spindle speed variation to suppress chatter is conducted. In 2011 a further research of spindle speed variation in chatter suppression was conducted. The research focus on to verify the efficiency of the optimal-linear spindle speed control by determine the best interval of time between subsequent changes of the spindle speed after receiving commands from the controller (*Kalinski and Galewski (2011)*).

The mathematical analysis in this field also takes place. *Tsao et al. (1993)* developed model taking the angular coordinates as variables instead of time followed by *Insperger and Stepan (2004)* , whose showed the semi-discretization method can effectively be used for stability analysis of turning at variable speed. Critical depth of cut can be increase for low speeds, but for high speed domain, there was no improvements.

Modelling the spindle speed variation of milling is more complex than turning but there still mathematical techniques to determine approximate dynamic properties. *Sastry et al. (2002)* used Fourier expansion and apply the Floquet theory to derive stability lobe diagram for race milling. Improvement for low spindle speed.

Later, *Zatarain et al. (2008)* propose a general method in the frequency domain to the problem. Show that varying spindle speed can effectively suppress chatter. It is recommended that the research of spindle speed variation requires a knowledge of the chatter frequency and the spindle speed.

Another approach to suppress chatter is to use time domain simulation which make it possible to obtain more detailed information like amplitude of vibration, chip thickness or cutting forces. The results of all these suppression technique gives a clear fundamental for the further research.

2.8 SUMMARY

To eliminate chatter, it must be detected first. Based on the research there were a lot of studies regarding chatter detection by using various type of sensor. The most frequently used sensor in the research is an accelerometer. Accelerometer provide a great information as its data have a close relationship with vibration and displacement. Oppositely, microphone sensor is rarely used. Surprisingly, microphone sensor do gives a very good data on chatter detection because it can react even for low immersion cut provided the sensitivity of the sensor is good enough.

Chatter occur because of the self-excited vibration. For chatter suppression, vibration damper or absorber is needed. It can be done in passive or in active approach. Passive suppression technique involves the manual modification of machines parameter to suit the particular cutting condition whereas active technique involves automatic adjustment.

Furthermore, active suppression technique consist of on-line and off-line technique. On-line technique is the method of collecting the real-time data during cutting process using sensor to give feedback for parameter re-adjustment. Offline method, oppositely, be made up of stand-alone controller, that programmed beforehand to vary the parameter. However, it will be more practical to control the spindle speed rather than other parameter for active chatter suppression. This is because in a real situation, changing the spindle speed do not interrupt the machining time and productivity rate as compared to depth of cut and feed rate.