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Suppression of Chatter in High Speed Milling Machine Using Spindle Speed Variation Method with Microphone Feedback PID Controller

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ABSTRACT – High speed milling (HSM) process limited by tool failure and dynamic instabilities due to the influence of relative vibration between tool and workpiece, so called chatter. Chatter vibration literally responsible for lower productivity and poor surface quality. In this paper, chatter occurrence during machining was suppressed using spindle speed variation (SSV) method via microphone online detection techniques. The initial experiment begins with constant material removal rate (MRR) where varies depth of cut, feedrate and spindle speed were analyzed using time and frequency domain. Later, microcontroller based PID algorithm was tested again in active mode. The result shows great differences in frequency.This proves that chatter occurrence during machining can be suppressed using spindle speed variation method with output feedback from PID controller. This also offers high speed milling usage industries with extra benefits of high productivity and can conserve time and money. Moreover, this method could enable providing high efficiency, accuracy, quality of final workpieces and eliminates semi-finishing process.

Introduction

High speed milling process contributes to numerous benefits as high efficiency and accuracy of final products, eliminate the secondary or semi-finishing process, cut off of costs and machining time. It also provides better surface finish, eliminates the needs of coolant, reduce tool load for finishing operation and small chips are produced for easily cleaning purposes. In recent years, manufacturing industry especially high speed milling usage industries expect high productivity rate and profit in short term of time. In parallel with it, the user also demands of a better quality of products and faster manufacturing process too. This demand unknowingly encourages the manufacturer to provide high efficiency, accuracy and quality of final product to satisfy their customers [1]. In this crucial situation, high speed milling usage industries facing huge problem. Concurrent studies on machining process explains that the process always limited by cutting tool failure and dynamic instabilities. This is due to the influence of relative vibrations between the cutting tool and the workpiece. This kind of self-excited vibration called as chatter. This phenomenon results in poor surface finish, dimensional inaccuracy and increase rate of tool wear of final product. This also may affect the machine life and tool life [2, 3].

In recent years, a chatter suppression method that attract most of the resesarchers attention is spindle speed variation method, whereby greater widhts of cut are achieved by modulating the spindle speed continuously. In order to increase the material removal rate a chatter suppression method based on continuous spindle speed variation is analysed. There are varies of spindle speed variation such as sinosoidal speed variation, whereby consists of three kinds of speed variation schemes: sinusoidal, increasing saw teeth and decreasing saw teeth. In additon, this trend that using sine wave to compensate chatter has poor stability in low frequency as well. In addition, multilevel random spindle speed variation is an another example of spindle speed variation method. Some researchers also developed a systematic stability analysis of spindle speed variation based on machining chatter model of nonlinear delay differential equation and numerically with the semidiscrezation method made of triangular and sinusoidal shape variations [2,4,5]. The spindle speed variation method consists in the superimposition of speed variations over the commanded constant spindle speed. As a result, the spindle speed variation method excites more frequencies than the constant machining with less energy [6]. This ensures that surface waves will be irregularly spaced. It prevents the regenarative mechanism of chatter from taking place. The effectiveness of the spindle speed variation method depends on the forcing input signal and on its parameters [7,8].

Apart from that, before implementing the spindle speed variation method, detection of chatter occurance durinf machining need to be considered. There were numerous research efforts have been conducted to develop methods and sensors in dectection of chatter. Based on the studies, in the aspect of methods the occurance of chatter can be suppressed by macroscopically check on how much the tool vibrates during machining. So that, a database can be build to avoid the problem rise again. On the other hand, data collected by using sensors help for analyze purpose about the occurance of chatter on each processing condition to prevent the chatter vibration. Furthermore, detection of chatter using sensors sufficiently contribute in compensation of chatter vibration compare with methods on a real time by considering in the aspect of time and efforts taken [9,10]. There are various of sensors used in online detection techniques to detect the instability. For instance force sensor, accelerometer and microphone. Among them, microphone sensor are used as chatter detection sensor widely because can easily measure the input signal without disturbing the system. Even though other sensors are very useful but still they have some limitations [11]. Moreover, microphone possible to be used as sensor to predict the instability due to the acoustic pressure emitted by a stucture during machining is proportional to the displacement of the tool. Otherwise, it must be noted that ambient condition such as environmental noise, reflection and near field which can distort the signal because the direct analogy exists between the microphone feedback in public address systems and chatter occurance during machining where both are time-delay feedback systems with stability that depends on the system gain [11,12].

In this paper, an experiment was conducted using 3-axis mini CNC milling machine to represent the high speed milling machine with accumulation of microphone sensor used as chatter detection medium. On the other hand, spindle speed variation method with implemented of PID algorithm was used to suppress the chatter vibration during machining. The frequency gained from the sensor was analysed step by step to indentify the dominant frequencies such as spindle frequency, machine frequency, tooth passing frequency and some other frequencies which appear during instabilities condition happens that contribute for chatter.

Method

The experiment begins with initial state where varies depth of cut, feedrate and spindle speed were discussed thoroughly as shown in Figure 1. A Variable Frequency Drive (VFD) controller as shown in Figure 2 used to drive a 220VAC, 7 Ampere and 1.5 kW spindle motor. The machine spindle speed is controlled by a potentiometer.
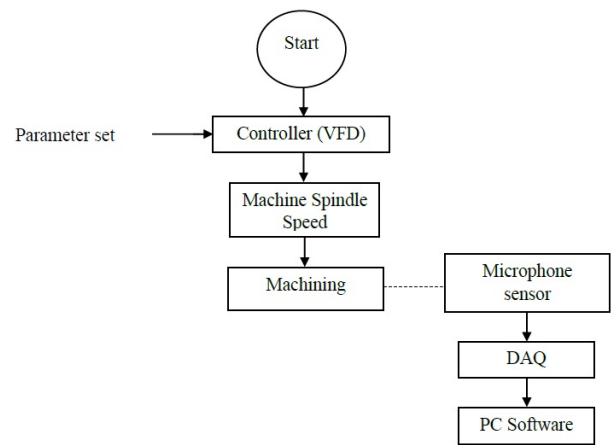
Figure 1. Experiment methodology flowchart.
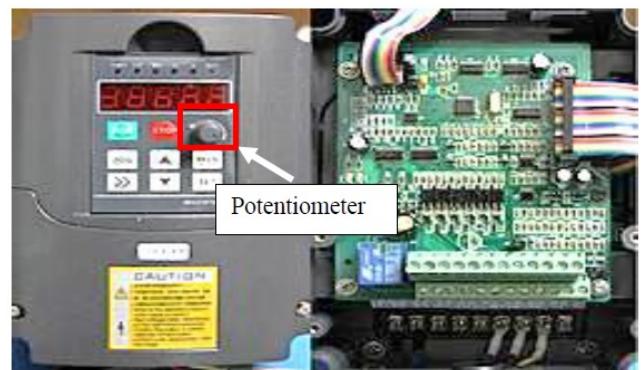
**Figure 2.** Variable Frequency Drive (VFD) Unit of the machine.

Machining parameters, such as depth of cuts is set beforehand. It is to ensure valid data can be compared with controlled parameters. Apart from that, the surrounding parameters also must be taken into consideration. To collect data from an acoustic sensor, the surrounding noise has to be suppressed. This is to ensure only valid data is collected. Thus, experiment must be conducted in an isolated room. The Experiment parameter is summarized in Table 1.

**Table 1.** Experiment parameter ranges.

Parameter	Minimum Value	Maximum Value
Depth of cut	0.1 mm	0.3 mm
Feed rate	2800 mm/min	3000 mm/min
Spindle speed	3000 rpm	20000 rpm

For chatter detection experiment stage, spindle speed of machine is controlled using a potentiometer, which control the voltage supplied to the spindle motor. The spindle speed value is detected using a built-in rotary encoder. Few experiments were designed to collect sufficient data to develop the active controller. The experiments consist of three parameters, namely axial depth of cut, feed rate and spindle speed. For every experiment conducted, data

is collected by microphone sensor by 2000 Hz sampling frequency. Every initial result was analyzed using Dasylab and Matlab software. DASYLab version 10.1 is used to record the data collected by microphone sensor during cutting process. The software consists of several block charts to channel the data and saved in ASCII file format which contains the time domain value from the sensor in Pascal (Pa). Figure 3 shows the screenshot of the DASYLab workspace that is use in this project.
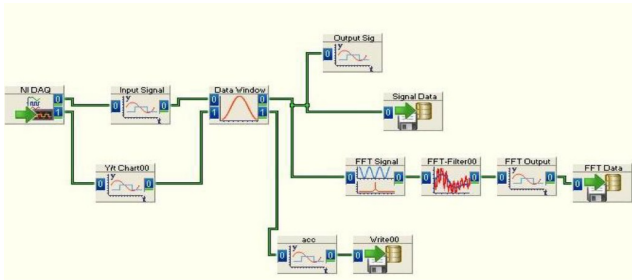

Figure 3. DASYLab workspace for the project.

(a)

(b)
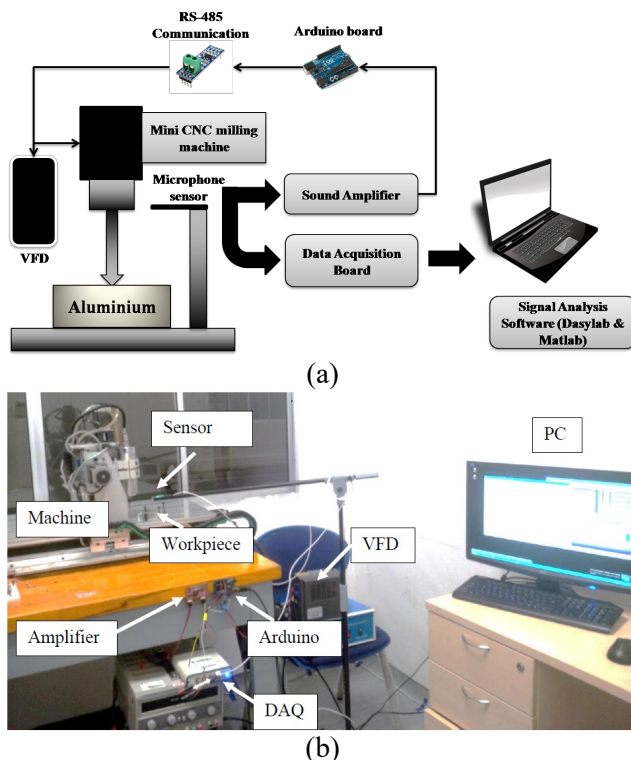
Figure 4. (a) Active control system configuration schematic diagram, (b) Actual active control system setup.

MATLAB software used to analyze the data saved from DASYLab to compute and show the data in graphical form using Fast Fourier transform technique. Other than that, a closed-loop active PID controller is set up using an Arduino microcontroller board. The experiment methodology for spindle speed variation method was designed as shown in Figure 4(a) while Figure 4(b) describes the actual setup of the

experiment for closed loop control experiment. Figure 5 shows model of PID closed-loop control system.
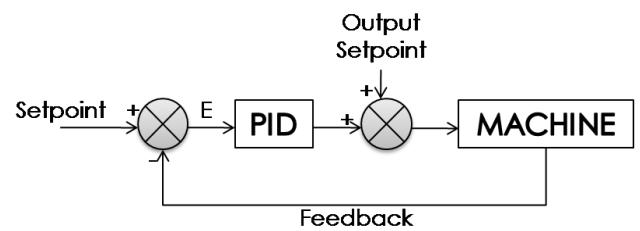
Figure 5. Model of PID closed-loop control system.

Data receive from the microphone sensor is in time domain. It is transform into frequency domain using Discrete Time Fourier Transform (DTFT) technique as shown in Equations 1, 2 and 3 to calculate the amplitude of spectral density at 400 Hz.

$$\text{Real Value} = \sum_{N-1}^{0} x[N] \cos(\omega NTs) \qquad (1)$$

$$\text{Imaginary Value} = \sum_{N-1}^{0} x[N] \sin(\omega NTs) \qquad (2)$$

$$\begin{aligned}&\text{Amplitude}\\&= \sqrt{(\text{Real Value})^2 + (\text{Imaginary Value})^2}\end{aligned} \qquad (3)$$

Where ω is the frequency at 400 Hz in radian, N, is the sample number and Ts, is the sampling time at 2000 Hz. From here, amplitude is set as input. Moreover, RS-485 module is used to communicate with VFD. In addition, RS-485 is a serial communicator that communicates with half-duplex on a single pair of wires, at a distance up to 1200 meter. Lines of codes is use to send a signal to VFD to change the spindle speed. In this project, the arduino microcontroller send data to VFD using 8N1 for ASCII MODBUS protocol that writes a function to override the current spindle frequency.

Results and Discussions

Time domain analysis is used to distinguish the pattern of sound pressure in different cutting condition based on its classification using a pre-set surface roughness threshold. It is the first data that can differentiate the chatter condition of those particular parameters. The pattern determines how loud the sound produces during the process. As the stability of the cutting condition increase, the amplitude ratio of sound pressure before cutting and during cutting process is increase by 1:1.5, 1:3, 1:4.5, 1:4.8 and, 1:5 for no vibration, average, poor, very poor and severe chatter respectively as shown in Figure 10 and Table 2.
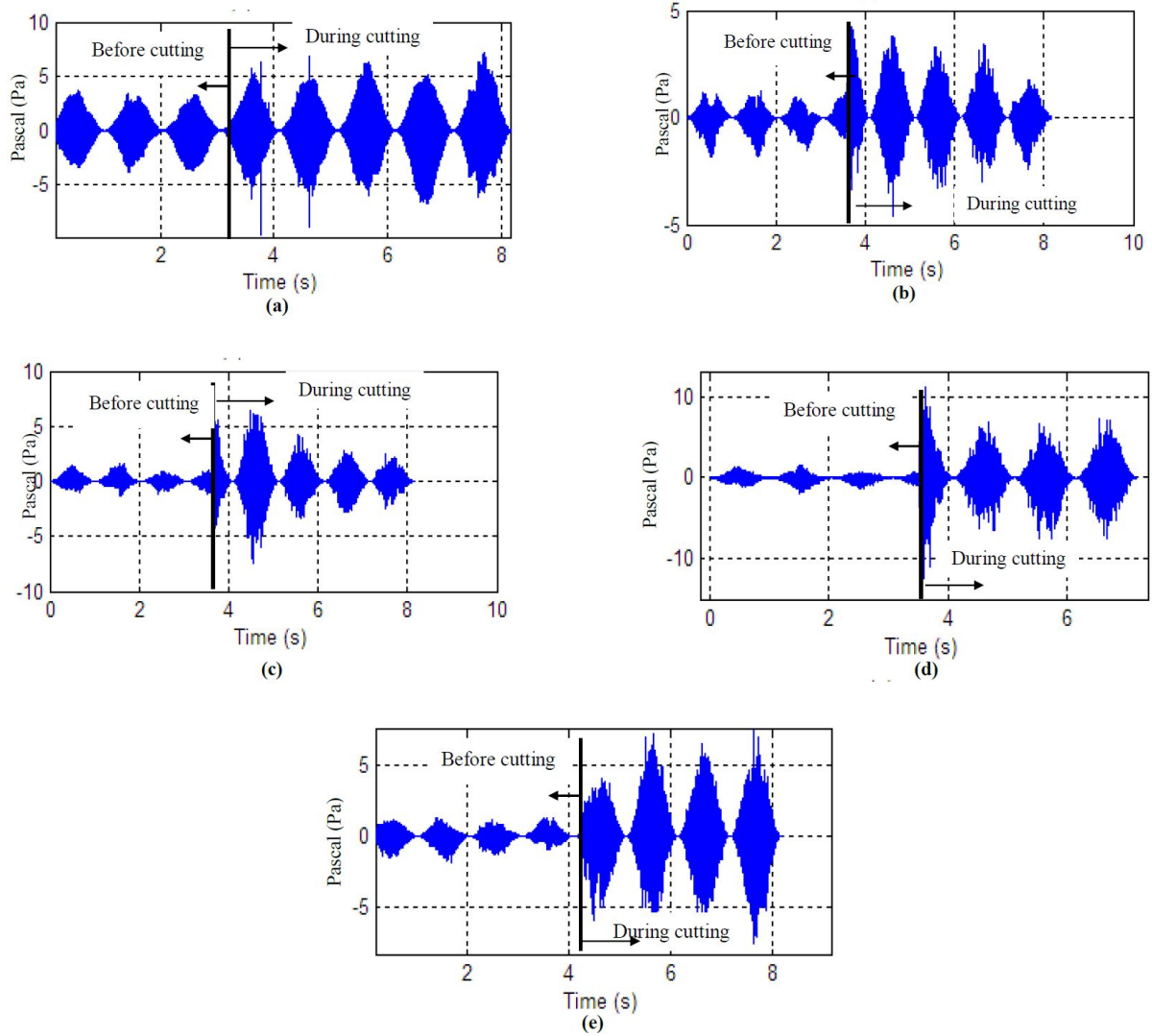
Figure 6. Sound pressure pattern of (a) no vibration, (b) average, (c) poor, (d) very poor, and (e) severe chatter condition.

Unfortunately time domain analysis is not enough to deduce that the particular process is stable or not. This is because time domain function consists of the summation of all the involved frequency in that sets of time. From this point, data is analyzed in frequency domain using FFT technique. Figure 7 shows the FFT result of non-stable and stable cutting process.

Table 2. Amplitude ratio of sound wave before and during cutting.

| Classification	Sound Amplitude ratio in Voltage (V)
No vibration	1 : 1.5
Average	1 : 3
Poor	1 : 4.5
Very poor	1 : 4.8
Severe	1 : 5
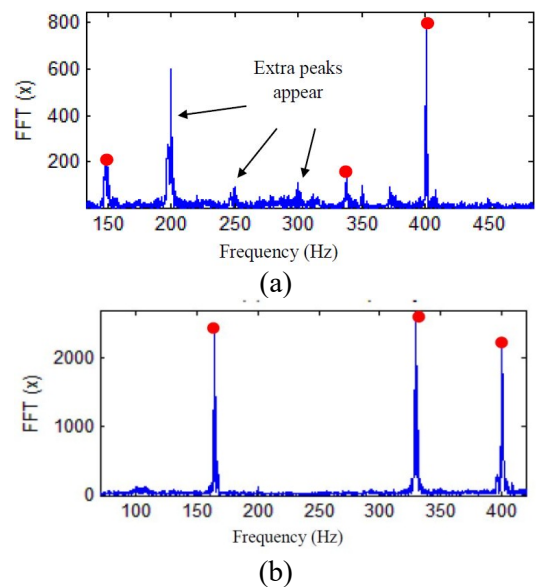
Figure 7: Example of FFT result for non-stable and stable condition for (a), and (b).

After that, based on the result, microcontroller based PID algorithm was drawn and tested again in active mode. 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 analyzed in time and frequency domain.
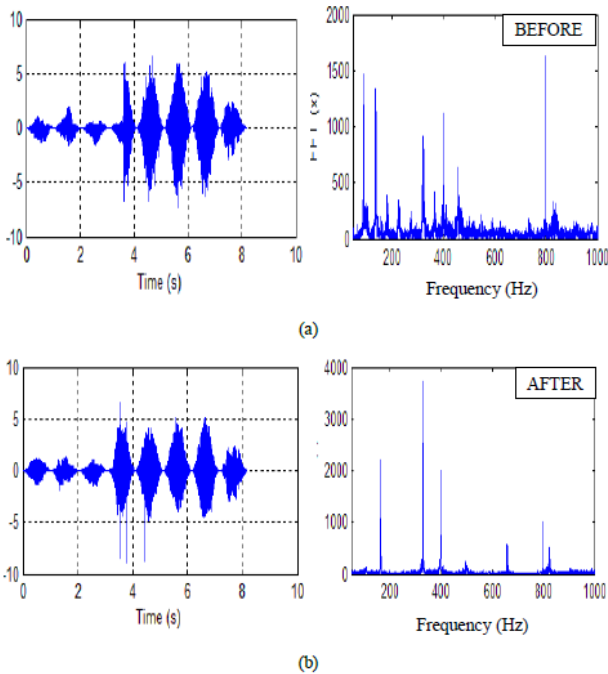
Figure 8: Time and frequency domain of 0.2 mm depth of cut before and after spindle speed control for (a) and (b).
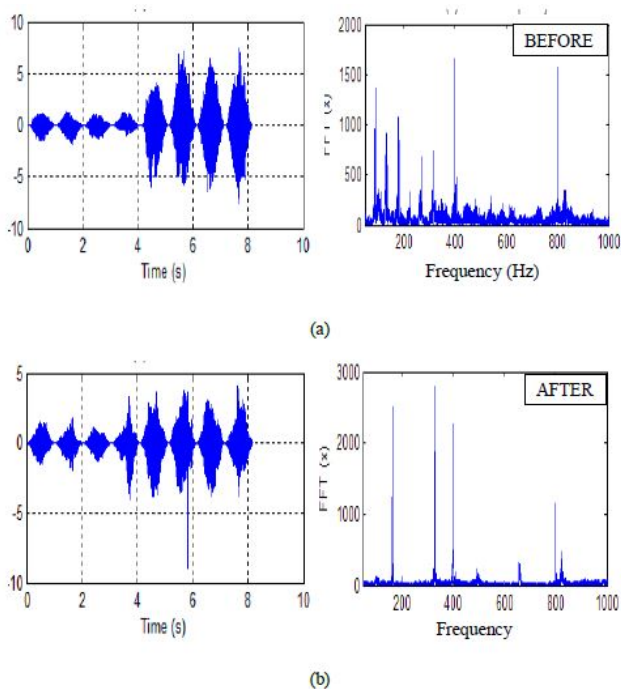
Figure 9: Time and frequency domain of 2900 mm/min feed rate before and after spindle speed control for (a) and (b).

Conclusion

The result gained from the experimens proves with crystel clear that occurrence of chatter between tool and workpiece during machining in high speed milling can be suppressed using spindle speed variation method with microphone feedback PID controller. This enables to eliminate chatter occurance by on-line. Hence, this contributes to the high speed milling usage industries by offering extra benefits such as high productivity and can conserve time and money. Moreover, this method could enable providing high efficiency, accuracy and quality of final workpieces and also eliminates semi-finishing process.

Acknowledgement

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