Integrated Chatter Avoidance and Minimum Quantity Lubrication Conditions for Chatter Vibration Problem in the Machining Process

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Abstract

This paper presents an experimental validation to compare stability lobes diagram between flood and minimal quantity lubrication condition in milling. The cutting condition is the most important factor contributing the machined work piece surface and in determining the acceptable cutting parameters for high productivity in metal cutting industries. Analytical and experimental identifications of the chatter frequencies in millingprocesses are presented.In the case of milling, there are several frequency sets arising from the vibration signals, as opposed to thesingle well-defined chatter frequency of the unstable turning process. Frequency diagrams are constructed analytically and attached to the stability charts of mechanical models of high-speed milling. The correspondingquasiperiodic solutions of the governing time-periodic delay-differential equations are alsoidentified with some milling experiments in the case of highly intermittent cutting.The predicted stability lobes are compared with the micro-milling force signalstransformed into the frequency domain. It is observed that the predicted stability limits result in goodcorrelation with the experimentally obtained chatter free conditions.

Introduction

In the aerospace, automotive, mould/die and general manufacturing industries, there isgreat pressure to ensure lower cost, greater productivity and improved quality in orderto encourage economic growth. However, machining productivity using a high materialremoval rate is inhibited by the dynamic deflection of tool and workpiece systems,which generates an unstable cutting force. This causes sudden large vibrationamplitudes where energy input exceeds the energy dissipated from the system,producing chatter. Chatter is a self-excited type of vibration that occurs in metal cuttingif the chip width is too large with respect to the dynamic stiffness of the system,especially when machining with a high material removal rate. In milling processes, thechip width is the axial depth of cut parameter. This produces a poor surface finish andhigh tool wear and can even damage machine tools as a result of the regenerative effect,the loss of the contact effect and the mode coupling effect. Regenerative chatter isperhaps the most common form of chatter [3] and will be the focus of this paper. Theregenerative chatter stability boundary is known as the stability lobe diagram and is afunction of depth of cut and spindle speed.

To predict the stability diagram, researchers have created various types of chatterprediction models, particularly time domain simulation [4], analytical solution of delaydifferentialequations with time periodic coefficients [5], time finite element analysis(TFEA) [6] and semi-discretisation method (SDM) [7]. For chatter suppression, passiveand active methods including vibration absorbers, damping, varying spindle speed and others has been applied. Passive methods are often suitable for a wide range offrequencies and machines compared to active methods.

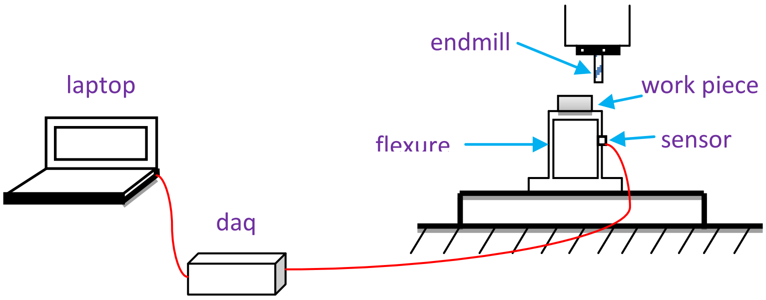
Nowadays, there are critical needs to reduce the usage of cutting fluid in machining process in order to reduce the environmental burden and economic cost [8].The rapid wear rate of cutting tools due to high cutting temperature is a critical problem to be solved in high-speed machining (HSM)of hardened steels. Near-dry machining such as minimum quantity lubrication (MQL) is regarded as one of the solutions to thisdifficulty.Comparing with dry cutting, the tool performance can be enhanced by MQL under all cutting speeds in this study. It is found that MQLcan provide extra oxygen to promote the formation of a protective oxide layer in between the chip–tool interface. This layer is basicallyquaternary compound oxides of Fe, Mn, Si, and Al, and is proved to act as diffusion barriers effectively. Hence, the strength and wearresistance of a cutting tool can be retained which leads to a significant improvement of tool life. It is found that there exists an optimalcutting speed at which a stable protective oxide layer can be formed. When cutting speed is lower than this speed, there is less oxide layerand the improvement of tool life is less apparent. As the cutting speed is far beyond the optimal value, the protective layer is absent andthe thermal cracks are apt to occur at the cutting edge due to large fluctuation of temperature. Resultantly, application of MQL isinappropriate in the extreme high-speed cutting condition irrespective of its little increase in tool life.

Furthermore, in MQL condition, which has cooling and lubricating effects, was found to have more significant influence in improving the tool life as compared to dry condition and its technique not only has cooling and lubricating effects on Nanocomposite coated tool, but also helps to form powerful protective layer[9].Generally speaking, the cutting fluid applied in themachining process is considered to act as cooling andlubricating agent, hence the cutting temperature can bereduced and the tool life and machined surface finish canbe improved. However, in the intermittent cutting such asmilling operation, especially in high-speed cutting, the largefluctuation of cutting temperature could cause thermalcracks on the cutting edge and subsequently leads to failureof a cutting tool due to edge fracture [10]. Besides, thereare serious environmental pollution and waste disposalproblems when flood coolants are used. In order toalleviate the above-mentioned negative effects, near-drymachining such as minimum quantity lubrication (MQL)has been developed and introduced in last decade. MQL properly employed can replacethe flooded coolant/lubricant environment which is presently employed in most of the cutting/machining applications; thereby not only themachining will be environmental friendly but also will improve the machinability characteristics [11].

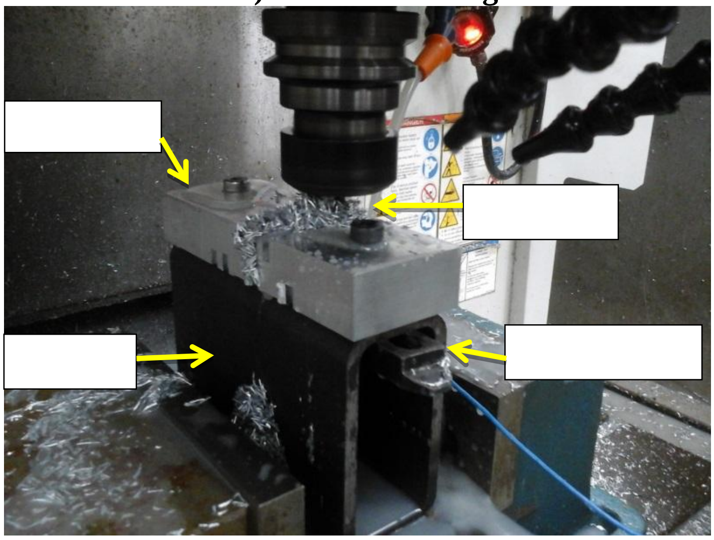
Experimental setting

A VF-1 three-dimensional vertical machining centre produced by Haas Automation, Inc. was selected for the experiments, having a maximum spindle speed of 8100 rpm.The flexure consists of a flexible steel basethat was machined from a rectangular cross-section beam welded to a rigid steel basesand cutting specimen mounted on top as used by Huyanan and Sims [41]. A 150.0 x50.0 x 50.0 mm^3 aluminium (7075-T6) cutting specimen was mounted on the flexure.This was to be down-milled at 10 percent radial immersion using a 5 mm diameter 4 flute end mill cutter. The tool was either of regular helix/pitch geometry, or optimisedgeometry using the procedure outlined previously.A set of spindle speeds and axial depths of cut were tested to determineif the cutting was stable or unstable. At the end of each cutting test, it was necessary toperform a clean-up pass to ensure a sufficient free surface for a later test.

During each cutting test, the flexure acceleration was measured the occurrence ofchatter, using a piezoelectric accelerometer (PCB 356C21) connected to a DAQDasylab10.0and laptop as shown in Figure 1.1. In addition, aFast-Fourier Transform (FFT) method in Matlab was applied to the acceleration timesamples to illustrate the acceleration spectra, using a Hanning window to reduce signalleakage.



a) Schematic Diagram



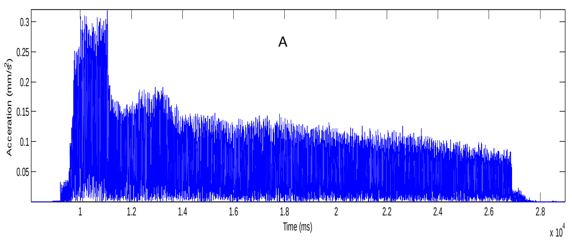
b) Sensor Location

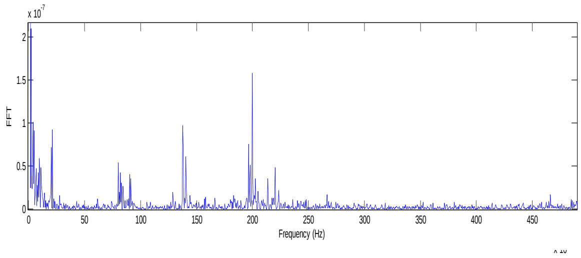
Figure 1.1 Arrangement for optimised tools experimental validation

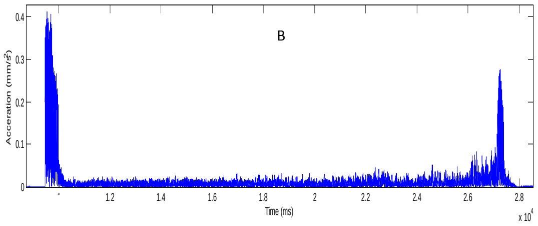
Acceleration signal identification

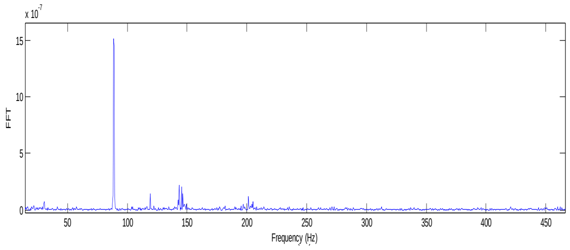
For the down-milling operation of the regular 4-flute end mill, the acceleration signalswere measured for regular and optimised tools performance. Figure 1.2shows thecutting tests were carried out in 3 cases for flood conditions: A (2750 rev/min, 5.0 mm), B(2750 rev/min, 10.0 mm) and C (5000 rev/min, 7.5 mm). For the minimal quantity lubrication condition, Figure 1.3 shows the results for 3 cases: D (1750 rev/min, 10.0 mm), E (2750rev/min, 7.5 mm) andF (5500 rev/min, 7.5 mm).Stable or chatter free cutting is demonstrated in cases A and C, as shown in Figures 1.2 respectively.

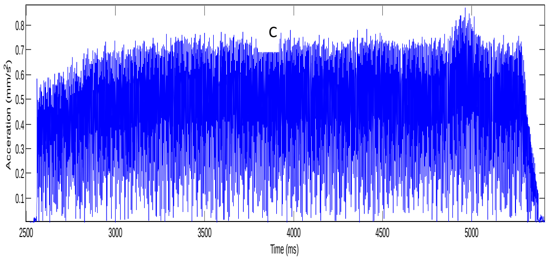
The FFT spectrum shows the frequency is dominated bytooth passing frequencies. These frequencies are lower than the flexure frequency,which related to cutting forces for each tooth beating the workpiece. However, chatter cutting is demonstrated in cases B,D and F as shown in Figures 1.2 and 1.3, respectively. The FFT spectrum shows the frequency is dominated by tooth passing frequencies. These frequencies are lower than the flexure frequency, which related to cutting forces for each tooth beating the work piece. For example of FFT spectrum in Figure 1.2 and 1.3(cases B, D and F), the chatter frequency was closed to the flexure natural frequency.

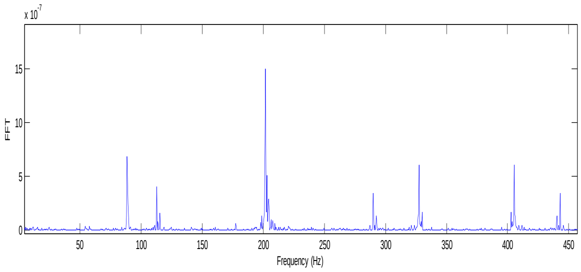




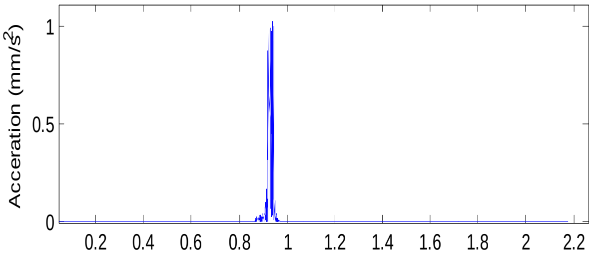


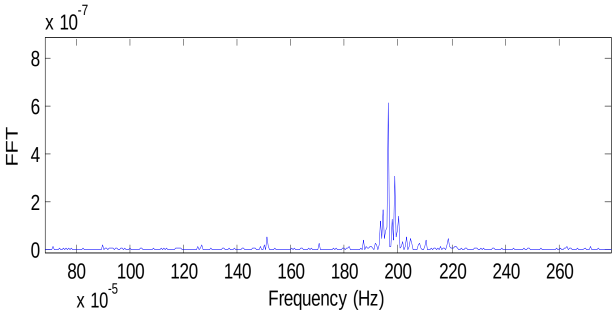


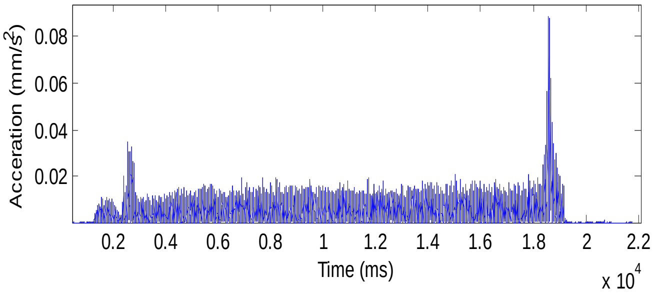


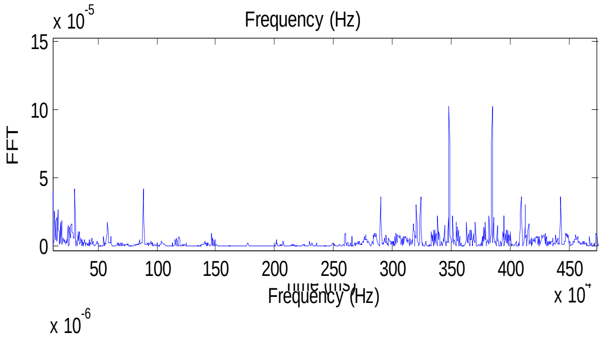


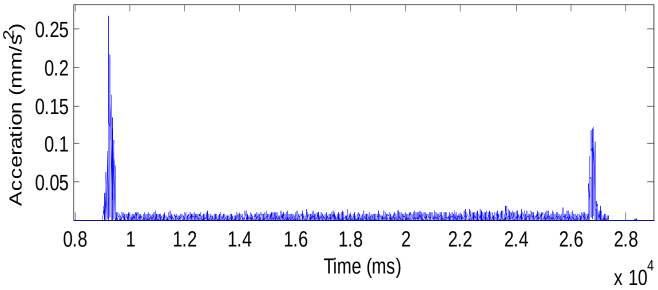
1.2 1/Rev and FFT-Spectrums for points A, B and C on flood condition

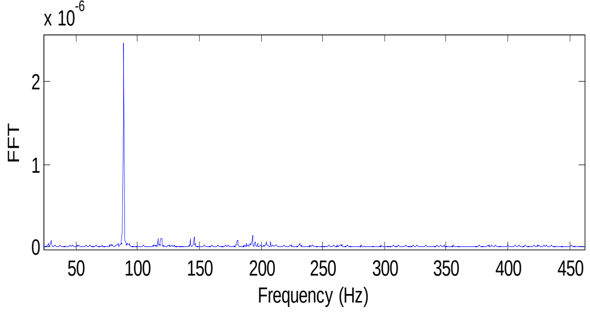




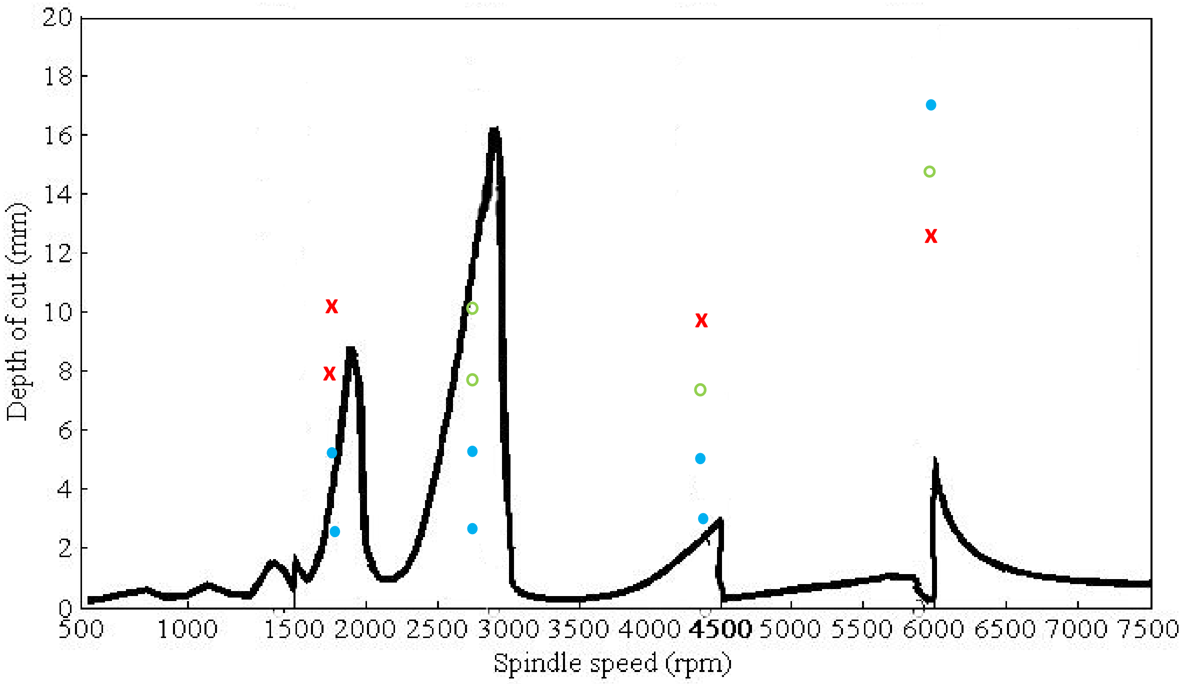




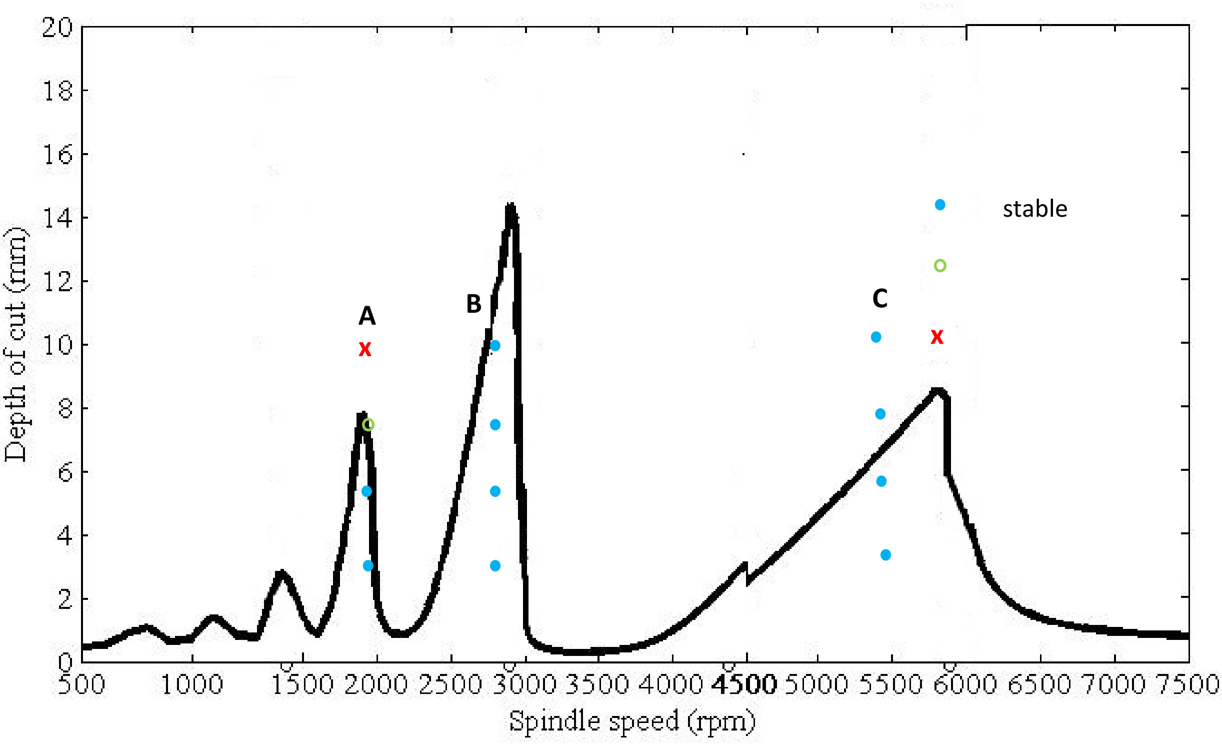




1.3 1/Rev and FFT-Spectrums for points D, E and F on MQL condition



1.4a) Stability lobes diagram of 500 – 7500 rev/min for flood condition



1.4b) Stability lobes diagram of 500 – 7500 rev/min for MQL condition

Chatter stability results

From identification of acceleration signal, cutting condition during experiment for eachcase is then obtained. Both theoretical prediction and experimental results werecompared for both tools and their chatter stability diagrams are now presented.Using SDM, the flood cutting condition chatter stability was predicted and superimposed withexperimental stability results at 10 percent radial immersion, as shown in Figure 1.4a. Itcan be clearly seen that there is an unstable area at high depth of cut, with critical depthof cut 10.0 mm, mostly at high spindle speed (1750-5750 rev/min).

For the down-milling operation with minimal quantity lubrication conditions of the regular 4-flute end mill, the result indicates agood agreement between predicted stability and experiment, as shown in Figure 1.4b.Stable or chatter free cutting conditions were shown outside the boundary of unstableregions.However, at high spindle speed, resonance occurred due tosimilarities of the chatter and spindle frequencies. It can be seen that the critical depth of cut for regular or original cutter wasexperimentally confirmed to be less than 2.5 mm.

Discussion

The stability of the process is obtained for a wide range of edgeradii, feed rates and run-out lengths. The results have been comparedwith experimentally measured force signals transformedinto the frequency domain where good correlation betweenmodelled and experimental results has been obtained.It can be seen that the optimised tool experimental stability results have been accuratelypredicted by SDM algorithm. These frequencies are lower than the flexure frequency, whichrelated to cutting forces for each teeth beating workpiece. The resonance corresponds tochatter frequency and the tooth passing frequency located close to each other.

Acknowledgements

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