Milling Chatter Prevention by Adaptive Spindle Speed Tuning

Nan-Chyuan Tsai, Din-Chang Chen, Rong-Mao Lee, and Bai-Lu Wang

Abstract**—**This paper presents how the real-time chatter prevention can be realized by feedback of acoustic cutting signal, and the efficacy of the proposed adaptive spindle speed tuning algorithm is verified by intensive experimental simulations. A pair of microphones, perpendicular to each other, is used to acquire the acoustic cutting signal resulting from milling chatter. A real-time feedback control loop is constructed for spindle speed compensation so that the milling process can be ensured to be within the stability zone of stability lobe diagram. Acoustic Chatter Signal Index (ACSI) and Spindle Speed Compensation Strategy (SSCS) are proposed to quantify the acoustic signal and actively tune the spindle speed respectively. By converting the acoustic feedback signal into ACSI, an appropriate Spindle Speed Compensation Rate (SSCR) can be determined by SSCS based on real-time chatter level or ACSI. Accordingly, the compensation command, referred to as Added-On Voltage (AOV), is applied to increase/decrease the spindle motor speed. By inspection on the precision and quality of the workpiece surface after milling, the efficacy of the real-time chatter prevention strategy *via* acoustic signal feedback is further assured.

Keywords**—**Chatter compensation, Stability lobes, Non-invasive measurement.

I. INTRODUCTION

SUPERIOR surface precision and high Material Removal Rate (MRR) are the most significant goals for milling process to be achieved concurrently. However, severe chatter arises if high MRR milling operation is engaged. In fact, chatter is a self-excitation phenomenon, which is provoked by the intermittent and less compliant cutting dynamics, but it determines, to some extent, the cutter life and the quality of finished workpiece surface. As depicted in Fig. 1, under ideal operation mode, phase shift between the current cutting pass and the previous is absent at all. Therefore, the cutting force can be almost retained constant owing to the chip thickness being kept consistent. On the other hand, once aforesaid phase shift is evidently present (see Fig. 1), drastic variations of chip thickness and discontinuous chips together lead to the intermittent alternation of cutting force and bring about chatter phenomenon. The stability lobe diagram, shown in Fig. 2, is usually utilized to describe the possibility and degree of chatter during milling operation [1]-[2], where the horizontal and vertical axes indicate the spindle speed and the axial cut depth respectively. The gray portion in Fig. 2 represents the unstable or chatter region.

In 1995, Altintas and Budak proposed an analytical prediction methodology to construct the stability boundaries for milling process, and both the chatter frequencies and the corresponding marginal depth of cut are well defined [3]. However, according to the experimental report by Faassen *et al.* [4], there is a certain un-negligible level of estimation errors for constructing stability lobes by applying this well-known methodology. Therefore, a modified approach was proposed by Solis *et al*. and the accuracy of stability estimation was considerably improved [5]. Though the concept of multi-frequency solution was ever reported to improve the evaluation accuracy on full stability boundaries [6]-[7], the approach by Solis *et al*. is still reckoned as the most acceptable off-line tool to establish the stability boundaries for milling operation.

In addition to applying the methodology by Solis for the estimation of stability boundaries, the cutting signal, traditionally treated as the noise, is utilized, filtered and converted as a key index for chatter analysis in this paper. Based on the concept of sound monitoring [8], the chatter prevention by feedback of acoustic cutting signal is proposed and verified by realistic cutting experiments in our work. The real-time feedback acoustic signal, having been filtered and converted into a quantitative signal index, which is named as Acoustic Chatter Signal Index (ACSI), and a spindle speed tuning command is then determined by the controller, synthesized in advance, according to the innovative ACSI level. Finally, the unstable COP is moved into the stable zone *via* the adaptive tuning of spindle speed. In order to examine the validity of the proposed methodology, intensive experiments are undertaken and the experimental results are presented at the end.

II. ACOUSTIC CHATTER SIGNAL AND QUANTITATIVE INDEX

For the purpose to quantify the feedback acoustic signal, the feedback signals of microphones are converted into the Acoustic Chatter Signal Index (ACSI) which is defined as follows:

$$L_I = \exp(0.5|\upsilon|) \tag{1}$$

Nan-Chyuan Tsai is with the Department of Mechanical Engineering, National Cheng Kung University, No. 1, University Road, Tainan 70101, Taiwan (phone: 886-6-2757575 ext. 62137; fax: 886-6-2369567; e-mail: nortren@mail.ncku.edu.tw).

Din-Chang Chen is with the Department of Mechanical Engineering, National Cheng Kung University (e-mail: e1491113@mail.ncku.edu.tw).

Rong-Mao Lee is with the Department of Mechanical Engineering, National Cheng Kung University, Taiwan (e-mail: n1894149@mail.ncku.edu.tw).

Bai-Lu Wang is with the Chung-Shan Institute of Science & Technology, Taoyuan County, Taiwan (e-mail: csist@csistdup.org.tw).

where the ACSI, L_I, is dimensionless. υ is the average voltage output of the mini-microphones in milli-volt (mV). The exponential function is employed to enhance the sensitivity of ACSI under higher voice intensity.

Since the chatter noise can be converted into the acoustic signal, the absolute value of average microphones outputs, $|\upsilon|$, is set to have two thresholds, i.e., 4.6mV and 2.2mV. These two voltage levels are referred to the noise intensities induced by the metal cutting, 12db and 8db, respectively [10]. That is, the background noises such as fluid flow and AC power have been filtered out so that 4.6mV and 2.2mV can be used to indicate severe chatter and moderate chatter respectively. In another words, the milling process is stable as long as the ACSI is smaller than 3 and becomes severe chatter if ACSI exceeds 10, shown in Fig. 3.

III. Strategy of On-Line Chatter Prevention

As aforesaid in Section I, for a certain proper MRR to be retained, the best strategy for chatter prevention is on-line tuning the spindle speed by feedback loop. Based on the constructed ACSI discussed in last section, an appropriate compensation for spindle speed is determined by the controller and realized *via* the signal data acquisition interface and the spindle motor. For different levels of chatter, different acceleration strategies for spindle speed are applied. As severe chatter occurs, it implies that the COP (marked by # in Fig. 4) is generally in higher axial cut depth and relatively far from stable region. Hence a higher speed tuning rate is required for the spindle to alter the location of COP # to be moved to COP $\hat{\#}$, i.e., in the stable region. However, since the spindle speed cannot be increased unlimitedly, the controller can only compensate the spindle speed up to the maximum rotation speed. On the contrary, a lower speed tuning rate is adopted for the case of moderate chatter (marked by * in Fig. 4). For the purpose to obtain better finished surface of the workpieces, the Spindle Speed Compensation Rates (SSCR) are set as 200 RPM/sec and 100 RPM/sec for COP # and COP * respectively in our work. The algorithm of Spindle Speed Compensation Strategy (SSCS) is shown in Fig. 5, where the ceiling of spinning speed is set as 3000 RPM due to the limit of the milling machine in our experiments.

IV. Verification of Acoustic Chatter Compensation

The test rig in our work including the milling machine (How-mau Machinery CO., LTD, Model CNC-K3) is depicted in Fig. 6. CBV in Fig. 6 is referred to the Control-Box Voltage for spindle motor, which is provided by the machine maker. AOV is referred to the Added-on Voltage which is the compensation command determined by the proposed controller in this paper. SCV is referred to the Synthesized Control Voltage which is the sum of CBV and AOV. It is noticed that the embedded control codes will not be overwritten. It means the proposed methodology provides more flexibility for machine-users to upgrade the chatter-prevention capability by inclusion of a couple of cheap devices, instead of buying new machines. The cutter employed in our work is of HSS (High Speed Steel) end, with diameter 7 mm and four cutting blades. The material of workpiece used in the test is Acrylic. As the milling process is engaged, the acoustic signal is continuously acquired by the mini-microphones and converted into electric voltage *via* signal processing interface *dSPACE* DS1104. The measure of cutting signal is then filtered and finally converted by ACSI so that the commands on spindle speed compensation, AOV, can be provided by the controller to real-time tune the spindle motor speed.

A. Cutting Operation Points (COPs)

It is well known that the chatter frequency is close to the natural frequencies of milling machine [5, 7]. Therefore, the natural frequencies of the milling machine have to be found in advance so that the stability lobe diagram can be constructed. By employing the methodology by Solis [7], the stability lobe of the milling machine is constructed, shown in Fig. 7, for chatter analysis and selection of COPs. To illustrate the efficacy of SSCS, two COPs, whose operation parameters are listed in Table I, are presented for up-milling test. The two COPs are both set in identical axial and radial cutting depth. The so called axial direction and radial direction are defined in Fig. 8 and referred to Z-axis and Y-axis respectively. The ACSI of milling tests at COP #1 and COP #2 are shown in Fig. 9 and Fig. 10 respectively. Since COP #1 is located in unstable zone (see Fig. 7), it is not surprising to find that the acoustic cutting signals are mostly above mild chatter threshold $\underline{L}_I = 3$ or even the severe threshold $\overline{L}_I = 10$. On the contrary, the acoustic cutting signal, shown in Fig. 10, are all below mild chatter threshold $\underline{L}_I = 3$. The micrographs of finished surface of the workpiece are shown in Fig. 11 and Fig. 12. It is obvious to notice that serious ridges, shown in Fig. 11, are evidently present for COP #1.

B. Experimental Results

The experimental results for up-milling under chatter prevention strategy are shown in Fig. 13. Suppose COP #1 is undertaken by the operator at the beginning. Therefore, the acoustic chatter cutting signal, provided by a pair of microphones, above $\overline{L}_I = 3$ is detected at time 1.2 sec. The chatter prevention algorithm SSCS, shown in Fig. 5, is activated at once. That is, an additional voltage (AOV, Added-on Voltage) determined by the controller is imposed on the spindle motor, as shown in Fig. 14. Accordingly, the spinning speed of the spindle is increased by 240 RPM, shown in Fig. 15. This implies that the operation point is leaving location of COP #1 and approaches COP #2 which is located in stable region so that the chatter between cutter and workpiece can be prevented.

Fig. 16 to Fig. 18 are the micrographs of the finished surfaces of the workpiece passing through three stages: SSCS not activated yet (start stage), SSCS engaged (transient stage) and SSCS completely operated (saturation stage). Fig. 16 is the finished surface corresponding to the milling operation for time interval of 0~2 sec in Fig. 13. Fig. 17 and Fig. 18 are the photographs of workpiece surface during time intervals of 6~8 sec. and 10~12 sec. respectively. It is obviously that the induced ridges, evidently present in Fig. 16, gradually become minor once the chatter prevention algorithm gets fully activated. In other words, the efficacy of the proposed SSCS is verified for chatter prevention.

TABLE I
PARAMETERS OF TWO COPS

Cutting Parameters				
COP	Axial Depth of Cut	Radial Depth of Cut	Spindle Speed	Feedrate
# 1 (Under Chatter)	2(mm)	0.1(mm)	1400(RPM)	100(MPM)
# 2 (Stable)	2(mm)	0.1(mm)	1700(RPM)	100(MPM)

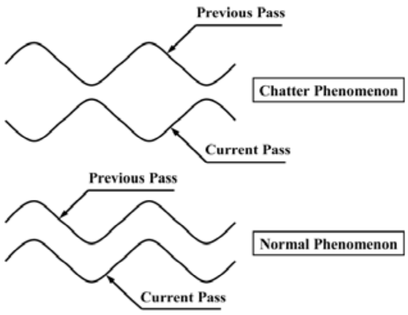

Fig. 1 Self-excitation Chatter

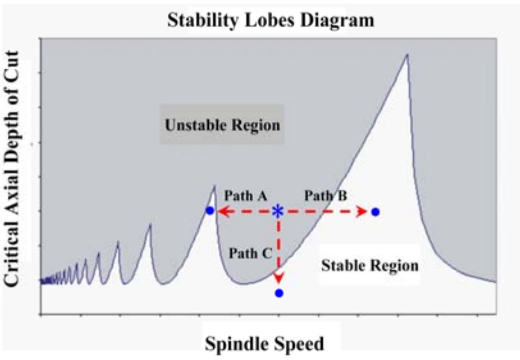

Fig. 2 Stability Lobes Diagram of Metal Cutting

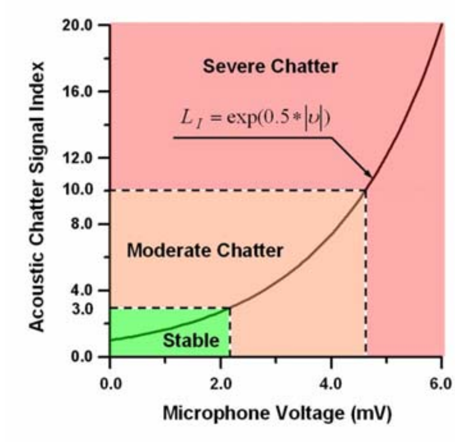

Fig. 3 Acoustic Chatter Signal Index (ACSI)

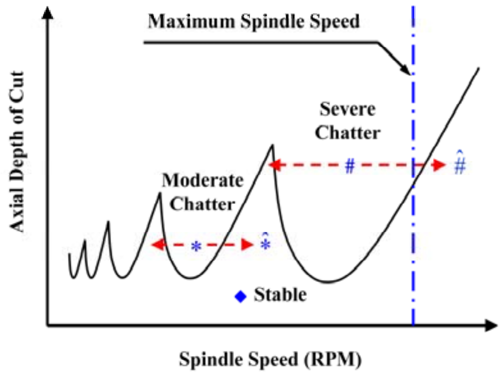

Fig. 4 Compensation Strategy for Spindle Speed

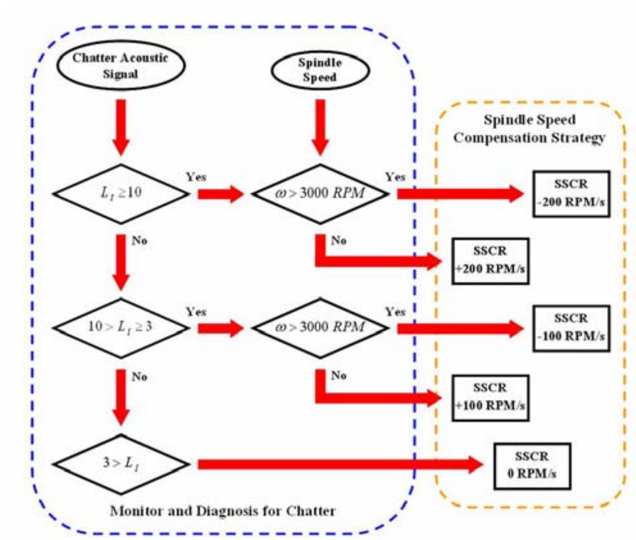

Fig. 5 Algorithm of Spindle Speed Compensation Strategy (SSCS)

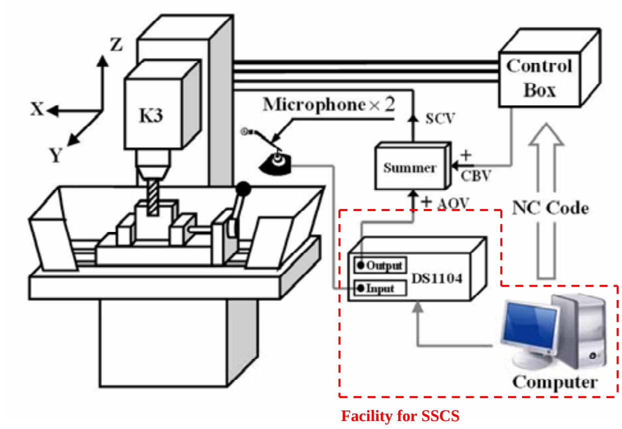

Fig. 6 Experiment Rig for Chatter Prevention Control

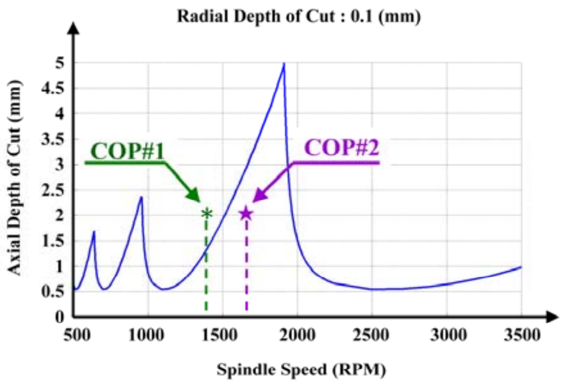

Fig. 7 Stability Lobe Diagram of the First Flexible Mode for CNC-K3

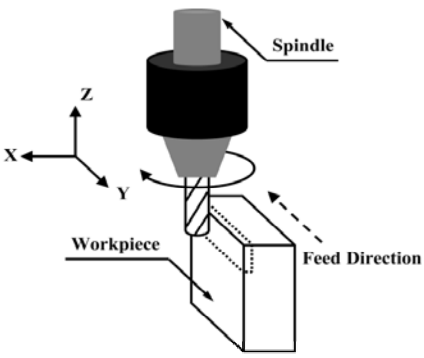

Fig. 8 Cutting Path of Milling Tests

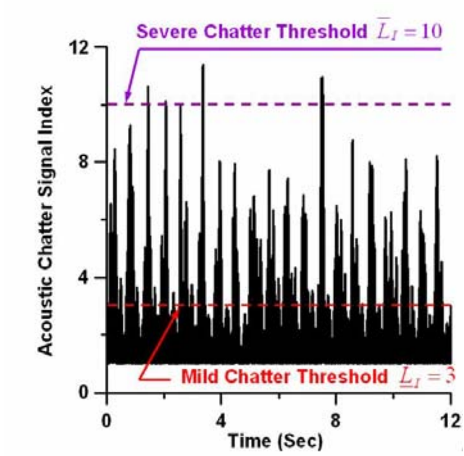

Fig. 9 ACSI of Milling Test for COP #1

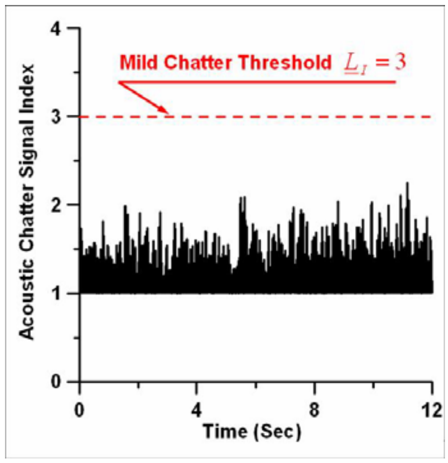

Fig. 10 ACSI of Milling Test for COP #2

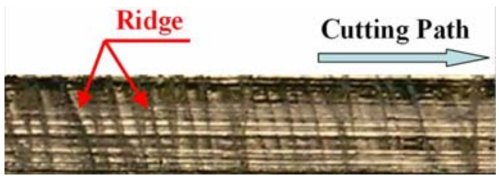

Fig. 11 Micrograph of Finished Surface by COP #1

Fig. 12 Micrograph of Finished Surface by COP #2

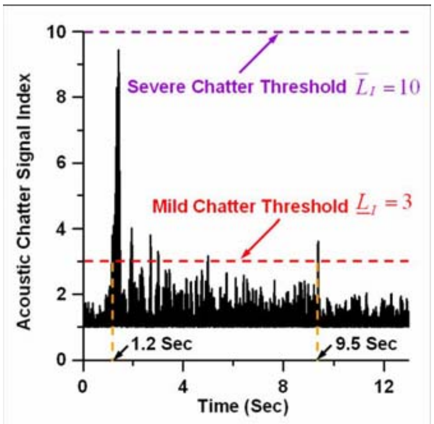

Fig. 13 ACSI of Milling Test under Chatter Prevention Strategy

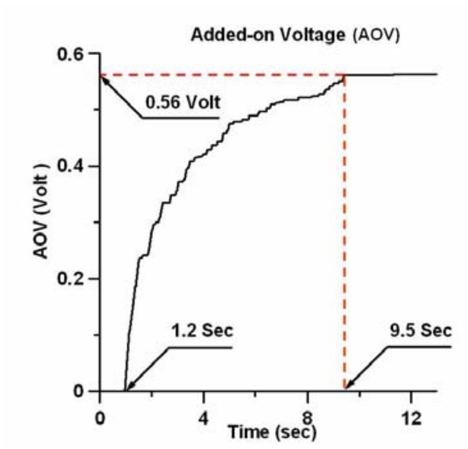

Fig. 14 Added-on Voltage Supplied to Spindle Motor

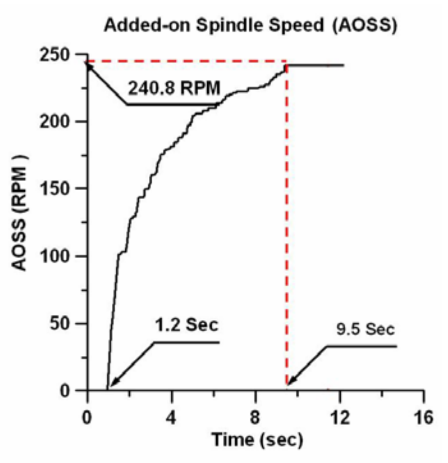

Fig. 15 Added-on Spindle Speed under SSCS

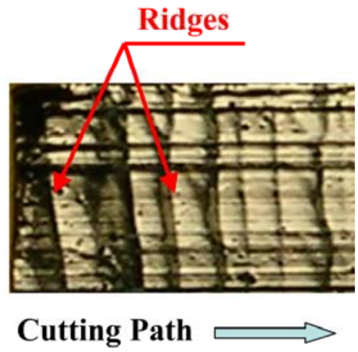

Fig. 16 Micrograph of Workpiece during 0~2 sec (SSCS not Activated yet)

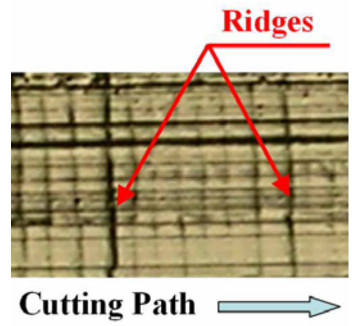

Fig. 17 Micrograph of Workpiece during 6~8 sec (SSCS being Engaged)

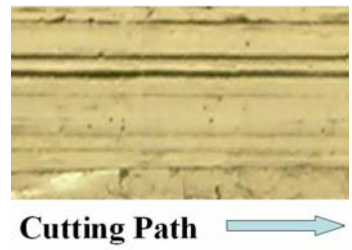

Fig. 18 Micrograph of Workpiece during 10~12 sec (SSCS Fully Operated)

V. Conclusion

From the cutting theorem, the milling process by discrete cutting blades is inevitable for the occurrence of chatter, due to the intermittent and less harmonious variations of cutting force. Although a lot of researches for chatter analysis have been presented, the COPs (Cutting Operation Points) during milling process are still considerably possible to be drifted into the unstable region owing to unpredictable disturbance. In this paper, an innovative control loop, based on Spindle Speed Compensation Strategy (SSCS) by using Acoustic Chatter Signal Index (ACSI), is proposed to prevent occurrence of milling chatter. Intensive experiments have been undertaken to verify the superiority of SSCS, to some extent, and outstanding improvement of the finished surface of the workpieces.

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