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ORIGINAL ARTICLE

# Chatter prevention for milling process by acoustic signal feedback

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**Abstract** This paper presents how 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 as well. The conventional approach to avoid chatter is to select a few appropriate operating points according to the stability lobes by experiments and then always use these preset cutting conditions. For most cases, the tremble measurement, obtained by accelerometers or dynamometers, is merely to monitor spindle vibration or detect the cutting force, respectively. In fact, these on-line measures can be more useful, instead of always being passive. Furthermore, most of these old-fashioned methodologies are invasive, expensive, and cumbersome at the milling stations. On the contrary, the acoustic cutting signal, which is fed into the data acquisition interface, Module DS1104 by *dSPACE*, so that an active feedback loop for spindle speed compensation can be easily established in this research, is non-invasive, inexpensive, and convenient to facilitate. In this research, both the acoustic chatter signal index (ACSI) and spindle-speed compensation strategy (SSCS) are proposed to quantify the acoustic signal and compensate 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. Accordingly, the compensation command, referred to as added-on voltage (AOV), is applied to actively tune the spindle motor speed. By employing commercial software MATLAB/Simulink and DS1104 interface module to implement the intelligent controller, the proposed chatter prevention algorithm is practically verified by intensive experiments. 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 examined and definitely assured.

**Keywords** Chatter compensation · Stability lobes · Non-invasive measurement

## 1 Introduction

Superior surface precision and high material removal rate (MRR) are the most significant goals for milling processes to be achieved concurrently. However, severe chatter arises if high MRR milling operation is engaged. Therefore, often low axial feedrate, which inevitably leads to low MRR, has to be adopted to avoid undesired severe trembles between cutters and workpieces. 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 the finished workpiece surface. As depicted in Fig. 1, under the ideal operation mode, the phase shift between the current cutting pass and the previous one is absent. Therefore, the cutting force can be almost kept constant owing to the chip depth being kept consistent. On the other hand, once the aforesaid phase shift is evidently present (see Fig. 1), drastic variations of chip depth and discontinuous chips together lead to the intermittent alternation of cutting force and bring about chatter phenomenon. Since chatter results in poor finish and degrades the quality of production, a few approaches to monitor and identify chatter dynamics were proposed in the past decade [1, 2].

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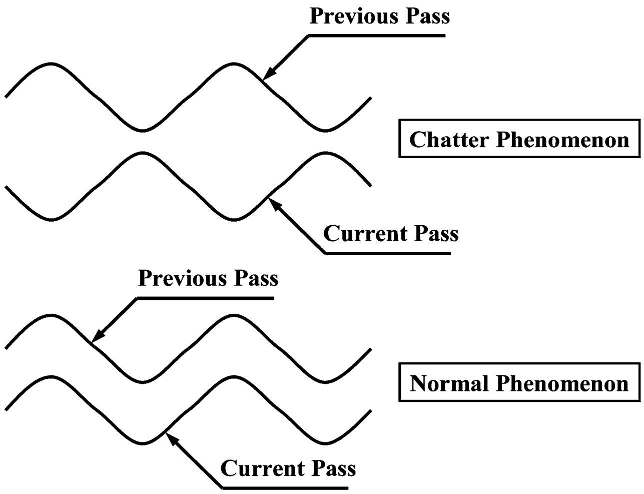


**Fig. 1** Self-excitation chatter

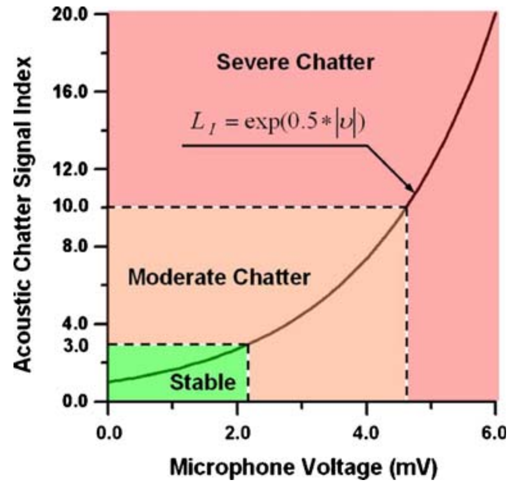


**Fig. 3** Acoustic chatter signal index (ACSI)

The stability lobe diagram, shown in Fig. 2, is usually utilized to describe the possibility and degree of chatter during the milling operation [3, 4], where the horizontal and vertical axes indicate the spindle speed and the axial cutting depth, respectively. The gray portion in Fig. 2 represents the unstable or chatter region. If the cutting operation point (COP) during the milling process drifts into the unstable zone due to any possible reasons, in general, there are three options to move the unstable COP to a stable region: reduce the axial cutting depth (path C in Fig. 2), adjust the spindle speed (path A or path B), or reset the feedrate. Compared with the strategies of cut depth reduction and feedrate reset, tuning of the spindle speed is relatively simpler, more efficient, and acceptable to be employed in practice [5, 6].

The construction of stability lobe diagram is accomplished mostly by theoretical analysis. 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 [7]. However, according to the experimental report by Faassen et al. [8], 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 [9]. Though the concepts of multi-frequency solutions and symbolic closed-form solutions were proposed to improve the evaluation accuracy on full stability boundaries [10–12], the approach by Solis et al. [9] is still reckoned as the most acceptable off-line tool so far to establish the stability boundaries for milling operation. However, the stability lobe diagrams have to be constructed first, prior to employing these methodologies [13–15]. Besides, it is noted that the technique of on-line acoustic

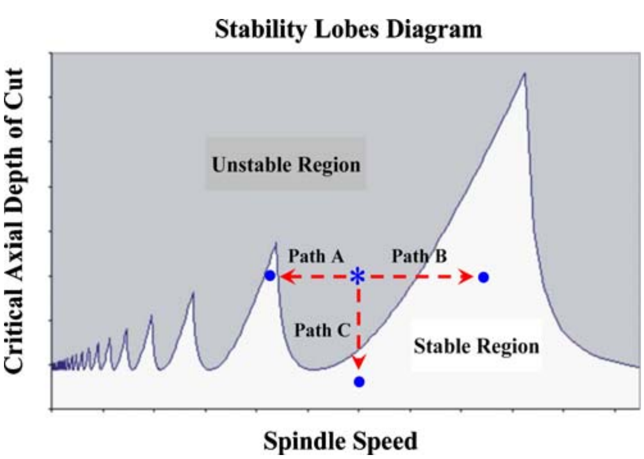


**Fig. 2** Stability lobes diagram of metal cutting

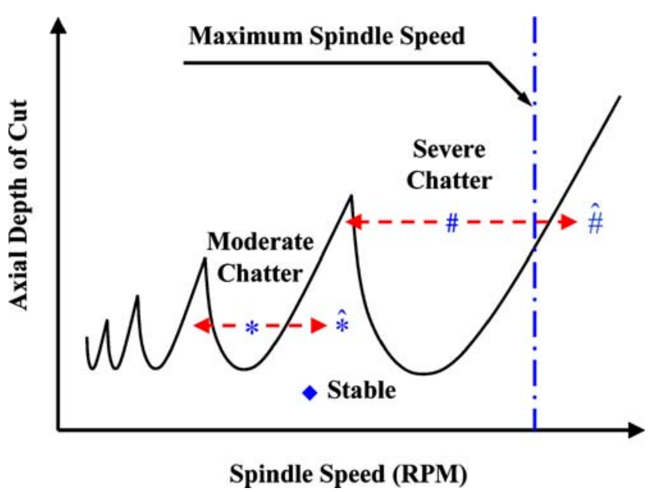


**Fig. 4** Compensation strategy for spindle speed

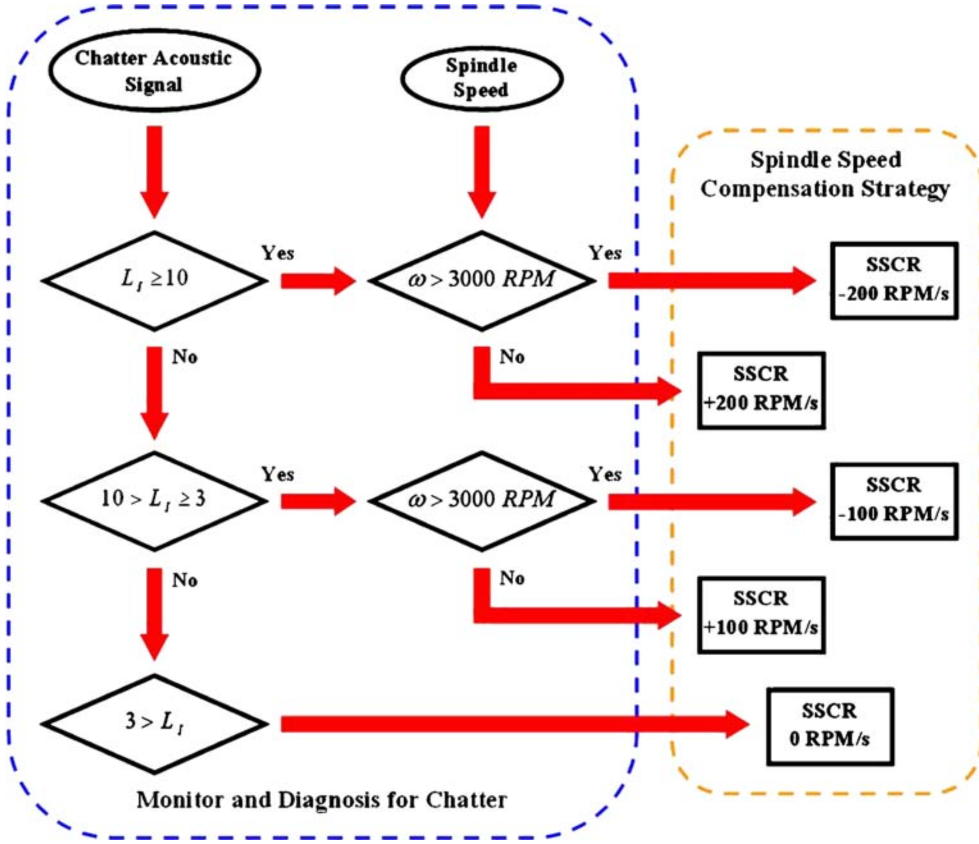


**Fig. 5** Algorithm of SSCS

signal analysis to prevent chatter has not been examined by realistic milling experiments.

In addition to the inclusion of the methodology by Solis for the estimation of stability boundaries, the cutting signal, traditionally treated as noise, is utilized to evaluate the instability degree of high-speed milling in our work. In comparison, the work of Morgan et al. is aimed at numerical analysis by fuzzy logic algorithms and determination of an appropriate COP [13]. On the contrary, our work is aimed at spindle speed compensation, without

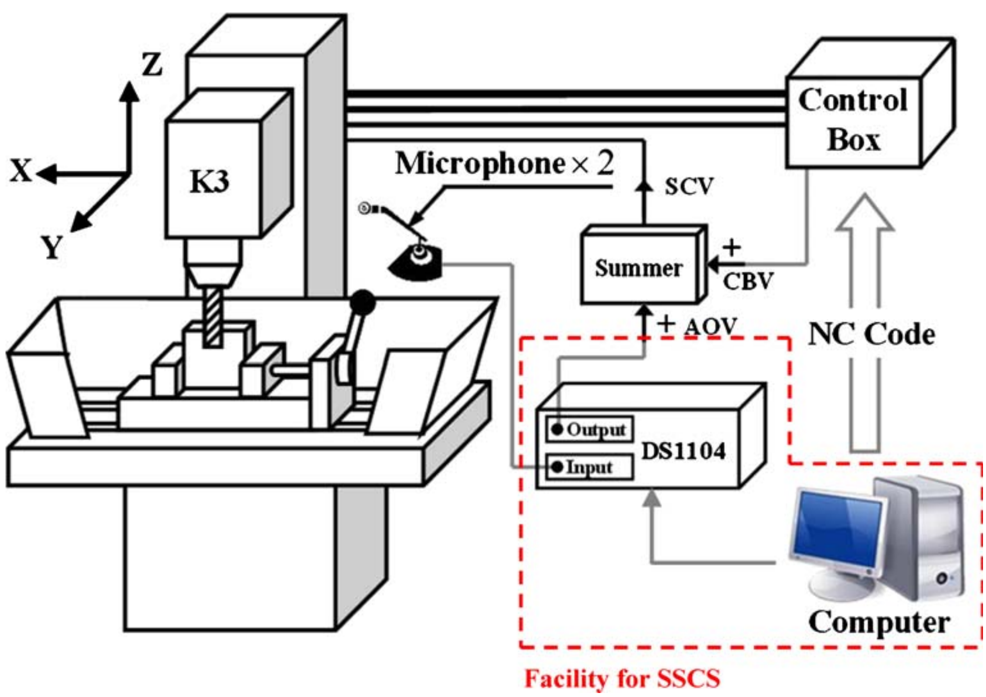


**Fig. 6** Experiment rig for chatter prevention control

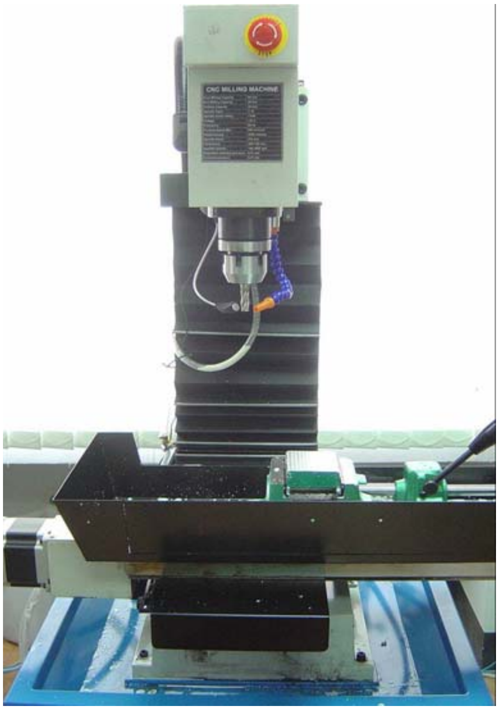


**Fig. 7** Photo of CNC-K3

needing the stability lobe diagram numerically. Especially, if the spindle speed is low, the interval of 0.5 mm axial cut depth in the work of Morgan et al. might be insufficient to obtain an accurate corresponding stability boundary, and it has to rely on the fuzzy algorithm. Instead, our work relies on acoustic chatter signal index (ACSI), which is recorded by real-time, even if the spindle speed is low.


**Fig. 8** Mini-microphone to acquire acoustic chatter signal

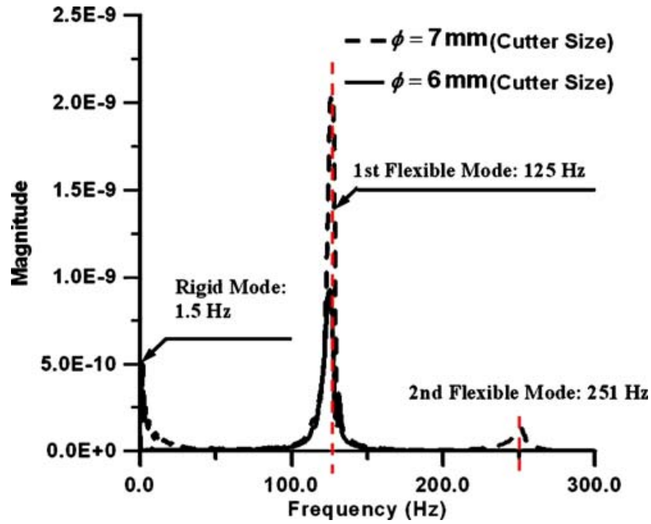


**Fig. 9** Frequency spectrum of milling spindle

Based on the concept of sound monitoring [10, 13–15], the real-time chatter prevention by feedback of the acoustic cutting signal is proposed and verified in our work. Conventionally, the boundary for the stability lobe diagram is mostly established by an off-line approach, and it tends to be altered, to some extent, once it is employed in realistic cutting. Therefore, the proposed algorithm in this paper is based on an “actual” real-time acoustic signal so that it would not be deadlocked by the “preset” stability lobe diagram. The real-time feedback acoustic signal, having been filtered to remove the components caused by power supply frequency, machine motion, and high-frequency noise, is converted into a quantitative signal index, which is named as ACSI, and a spindle speed tuning command is then determined by the controller, synthesized in this paper, according to 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 under-

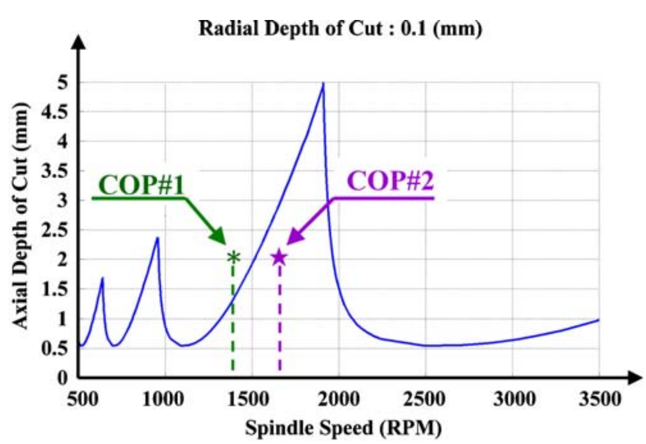


**Fig. 10** Stability lobe diagram of the first flexible mode for CNC-K3

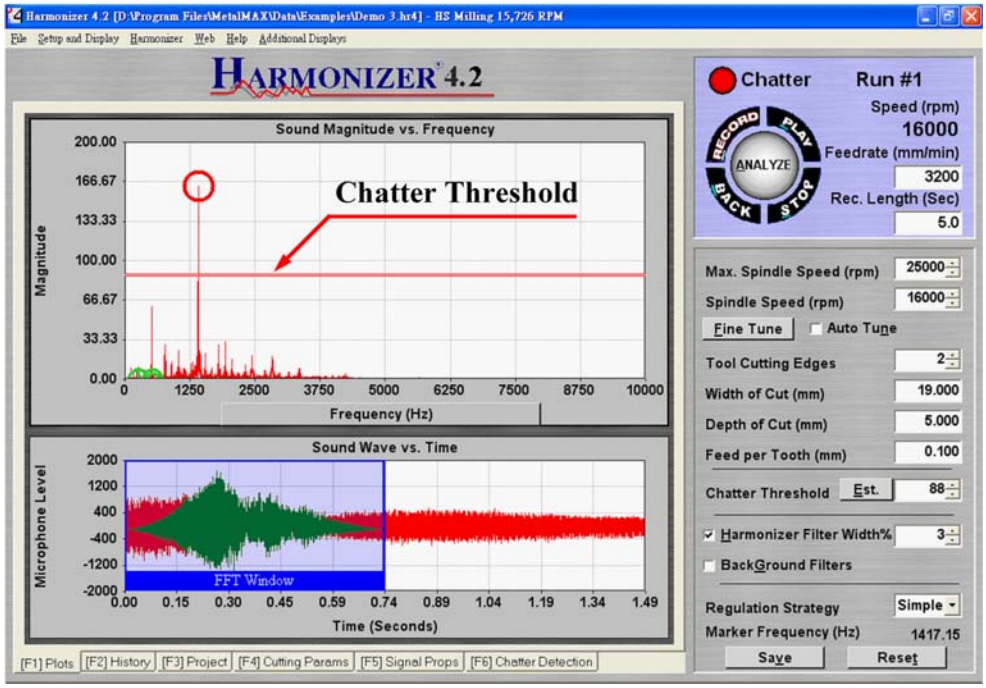


**Fig. 11** Graphic user interface (GUI)_ Harmonizer

taken and the experimental results are presented at the end. The proposed chatter-prevention strategy does not suffer from poor accuracy of the stability lobe diagram, constructed either by theory or experiments. The stability lobe diagram is not numerically required at all. Therefore, it becomes much more flexible for wide-range cutting conditions. Otherwise, a new stability lobe diagram, like that in Fig. 2, is needed as long as a different (or second) cutting condition is undertaken (e.g., change of cutter). In comparison, Morgan et al. need to establish a vast amount of experimental data and store it in the expert system beforehand [13].

## 2 Acoustic chatter signal and quantitative index

For the purpose of quantifying the feedback acoustic signal, the feedback signals of microphones are converted into the ACSI, which is defined as follows:

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

where the ACSI, $L_I$, is dimensionless. $v$ is the average voltage output of the mini-microphones in millivolts (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, $|v|$, is set to have two thresholds, i.e., 4.6 and 2.2 mV. These two voltage levels are referred to the noise intensities induced by the metal cutting, 12 and 8 db, respectively [16]. That is, the background noises such as fluid flow and AC power have been filtered out so that 4.6 and 2.2 mV can be used to indicate severe chatter and moderate chatter, respectively. In other words, the milling process is stable as long as the ACSI is smaller than three and becomes severe chatter if ACSI exceeds ten, as shown in Fig. 3.

## 3 Strategy of on-line chatter prevention

As mentioned in Section 1, 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 the last section, an appropriate compensation for spindle speed is determined by the

**Table 1** 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) | 1,400 (RPM) | 100 (MPM) |
| # 2 (stable) | 2 (mm) | 0.1 (mm) | 1,700 (RPM) | 100 (MPM) |

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 the 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 of obtaining better-finished surface of the workpieces, the spindle speed compensation rates (SSCR) are set as 200 and 100 RPM/s 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 the spinning speed is set at 3,000 RPM due to the limit of the milling machine in our experiments. By employing SSCS, the milling chatter is suppressed rapidly and verified by intensive experiments, which will be addressed in the next section.

## 4 Verification of acoustic chatter compensation

The test rig in our work including the milling machine (How-mau Machinery, Model CNC-K3) is depicted in Fig. 6. CBV in Fig. 6 refers to the control-box voltage for the spindle motor, which is provided by the machine maker. AOV refers to the added-on voltage, which is the compensation command determined by the proposed controller in this paper. SCV refers to the synthesized control voltage, which is the sum of CBV and AOV. It is noted that the proposed compensation strategy does not need to overwrite the initially downloaded control codes. The control box by the milling machine maker is 100% preserved. All we add is the PC with interface board to provide another “tuning voltage” AOV. It 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 photo of CNC-K3 is shown in Fig. 7. The cutter employed in our work is of high-speed steel (HSS) end, with a diameter of 7 mm and four cutting blades. The material of the workpiece used in the test is acrylic. As the milling process is engaged, the acoustic signal is continuously acquired by the mini-microphones, shown in Fig. 8, and converted into electric voltage via signal processing

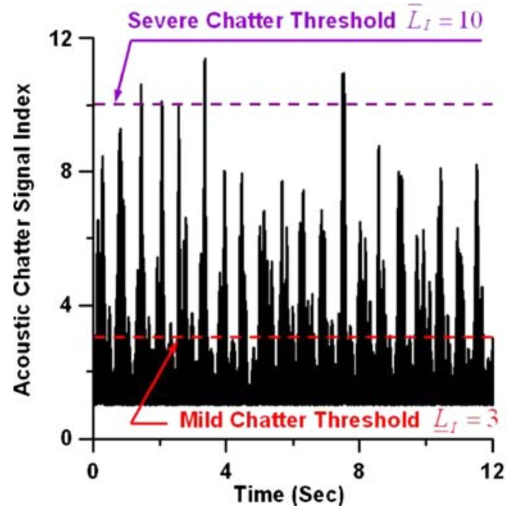


**Fig. 13** ACSI of milling test for COP #1

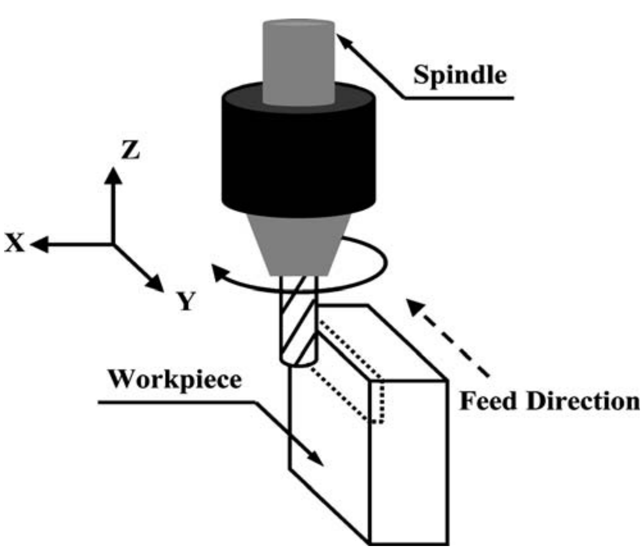


**Fig. 12** Cutting path of milling tests

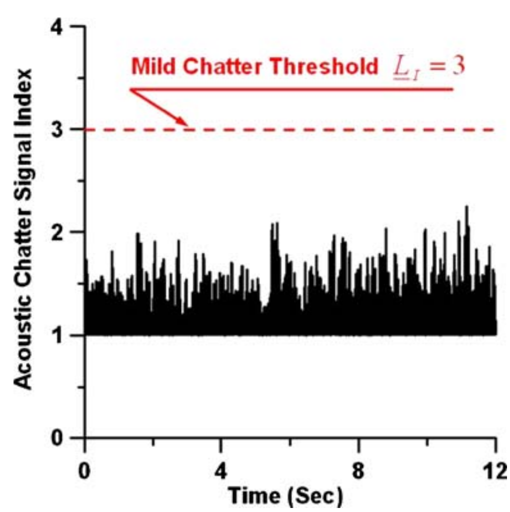


**Fig. 14** ACSI of milling test for COP #2

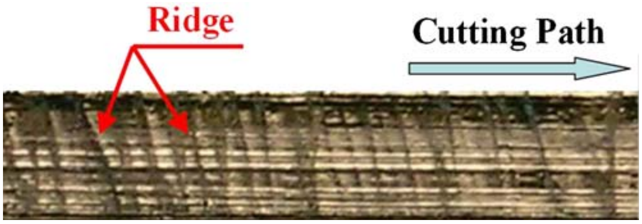


**Fig. 15** Micrograph of finished surface by COP #1

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 tune the spindle motor speed in real time.

## 4.1 Cutting operation points (COPs)

It is well known that the chatter frequency is close to the natural frequencies of the 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 of Solis [7], the natural frequencies and stability lobe diagram for CNC-K3 are shown in Figs. 9 and 10, respectively. Since the natural frequency, 1.5 Hz, of the rigid mode is relatively low, with respect to the nominal spindle speed, under the milling process, the stability lobe of the first flexible mode is constructed for chatter analysis and selection of COPs. In order to further ensure the COPs selected from stability lobes are practically applicable for the milling machine, the commercial software *Harmonizer*, shown in Fig. 11, is well set up in CNC-K3 and employed to examine the validity of COPs by realistic milling tests.

To illustrate the efficacy of SSCS, two COPs, whose operation parameters are listed in Table 1, 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. 12 and referred to as Z- and Y-axes, respectively. The ACSI of milling tests at COP #1 and COP #2 are shown in Figs. 13 and 14, respectively. Since COP #1 is located in an unstable zone (see Fig. 10), it is not surprising to find that the acoustic cutting signals are

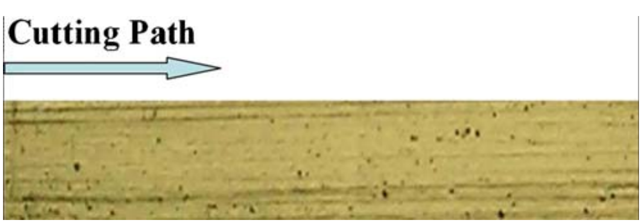


**Fig. 16** Micrograph of finished surface by COP #2

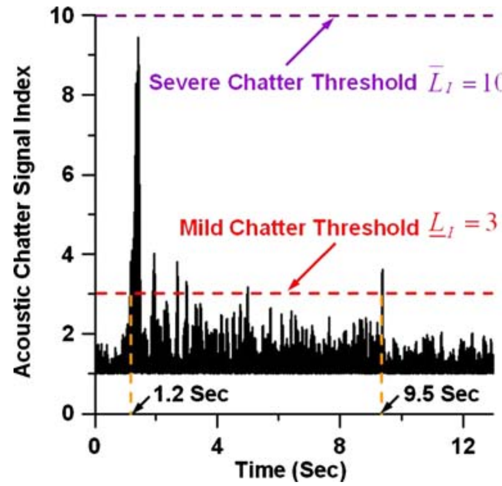


**Fig. 17** ACSI of milling test under chatter prevention strategy

mostly above mild chatter threshold $\underline{L}_I = 3$, or even the severe threshold $\overline{L}_I = 10$. On the contrary, the acoustic cutting signals, shown in Fig. 14, are all below the mild chatter threshold $\underline{L}_I = 3$. The micrographs of the finished surface of the workpiece are shown in Figs. 15 and 16. It is obvious that serious ridges, shown in Fig. 15, are evidently present for COP #1.

## 4.2 Experimental results

The experimental results for up-milling under chatter prevention strategy are shown in Fig. 17. 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 s. The chatter prevention algorithm SSCS, shown in Fig. 5, is activated at once. That is, an additional voltage (AOV) determined by the controller is imposed on the

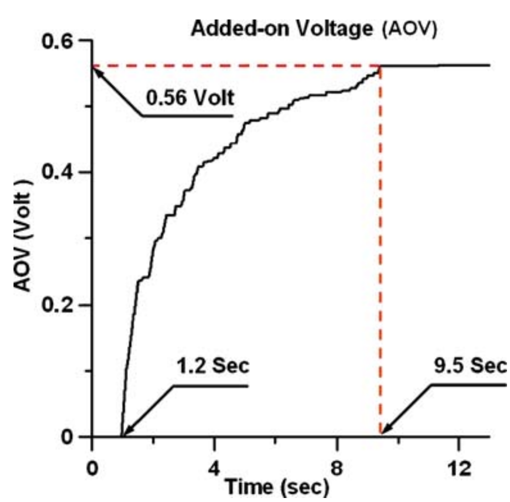


**Fig. 18** AOV supplied to spindle motor

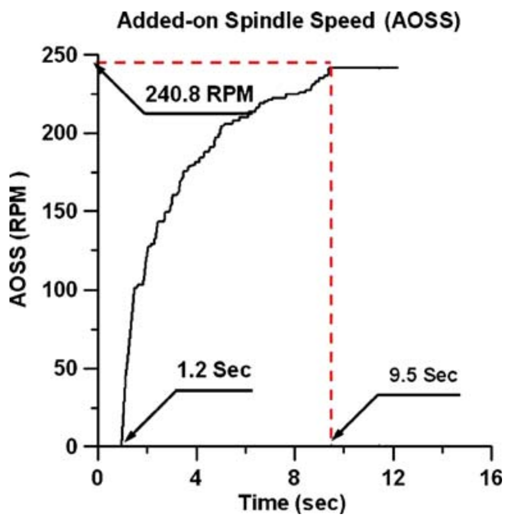


**Fig. 19** Added-on spindle speed under SSCS

spindle motor, as shown in Fig. 18. Accordingly, the spinning speed of the spindle is increased by 240 RPM, shown in Fig. 19. This implies that the operation point is leaving the location of COP #1 and approaches COP #2, which is located in a stable region so that the chatter between cutter and workpiece can be prevented.

Figures 20, 21, and 22 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). Figure 20 is the finished surface corresponding to the milling operation for time intervals of 0–2 s in Fig. 17. Figures 21 and 22 are photographs of the workpiece surface during time intervals of 6–8 and 10–12 s, respectively. It is obvious that the induced ridges, evidently present in Fig. 20, 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.

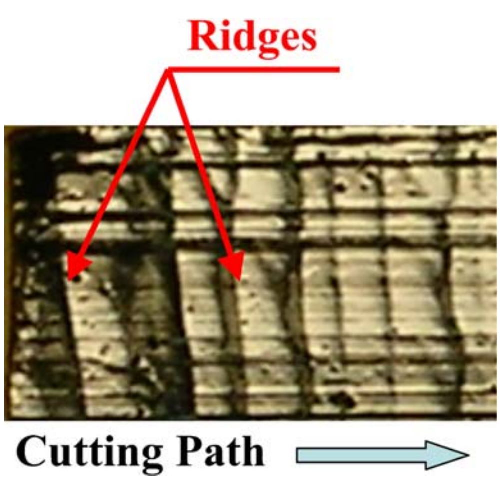


**Fig. 20** Micrograph of workpiece during 0–2 s (SSCS not activated yet)

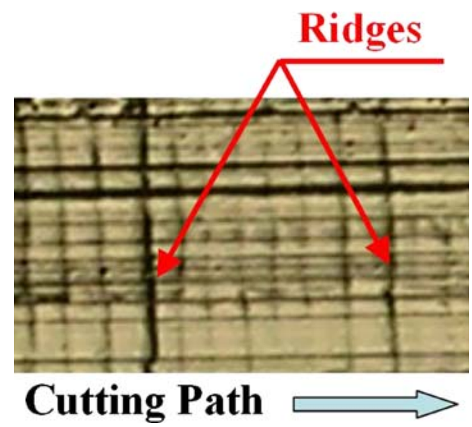


**Fig. 21** Micrograph of workpiece during 6–8 s (SSCS being engaged)

## 5 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 research for chatter analysis has been presented, the COPs 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 SSCS by using 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.

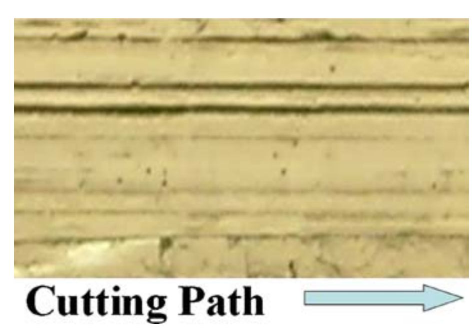


**Fig. 22** Micrograph of workpiece during 10–12 s (SSCS fully operated)

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