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Study of an Efficient Real-Time Monitoring and Control System for BUE and Cutter Breakage for CNC Machine Tools

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If machining abnormalities, such as build-up-edge and cutter breakage, occur during machining, serious damage on the workpiece surface and deterioration of production efficiency will happen, and cause additional energy consumption for rework and increase the manufacturing cost. To minimize the effects, an on-line diagnosis method with use of Fast Fourier Transform and algorithm of short-time signal variation analysis was developed to analyze the vibration signals to quickly detect the two abnormalities in this study. In addition, the real-time machining information from CNC controller was extracted through a bi-lateral communication module to prevent misdiagnosis. The control commands were automatically generated by the proposed system and directly sent to the CNC controller to stop the machine for cutter replacement. Without complex computation, the system can detect the occurrence of BUE or cutter breakage within 1 second and complete machine control within 3 seconds. The system can instantly transmit and save the real machining information and diagnosis/control results to the remote central monitoring platform for further process improvement. With use of TCP/IP communication protocol the central monitoring platform can remote log into the on-site monitoring computer to directly operate the diagnosis/control system. Experimental results showed the feasibility and effectiveness of the proposed system.

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1. Introduction

Precision milling is one of the major manufacturing processes for modern industry. If machining abnormalities, such as build-up-edge (BUE) and cutter breakage, occur during machining, serious damage on the workpiece surface and deterioration of production efficiency will happen, and cause additional energy consumption for rework and increase the manufacturing cost. To avoid/alleviate the damages or invalid machining for productivity concern, the abnormalities should be detected and controller in early stage. The earlier the abnormalities are detected, the less workpiece damages or waste of machining time can be achieved. Therefore, an effective monitoring and control system that can early detect the occurrence of BUE and cutter breakage and directly stop the machine for cutter replacement is necessitated. To match the requirement of modern production lines, the monitoring and control system should be designed with the characteristics of high computation efficiency, friendly communication, and internet-based remote control.

Many researches had been devoted for machining abnormality analysis and its damage prevention. Tlusty[1] developed a nonlinear force model for milling chatter and analyzed stability through numerical simulation. Chen[2] collected acceleration signals and force signals during the milling process, and stored those signals in the computer. Subsequently, the characteristic values of those signals were calculated and mixed through addition, multiplication, division, and vector projection. Finally, the mixed characteristic values were used as inputs of neural network analysis to diagnose the condition of the milling process. Some studies were made to predict the occurrence of build-up-edge and cutter breakage. With taking cutting and thrust forces, chip flow, chip up-curl radius, chip thickness, and tool-chip contact length into account, Fang[3] proposed a slip-line model for prediction of BUE. Panda et al.[4] used back-propagation neural network to predict the tool wear to avoid the occurrence of cutter breakage. Zhang[5] simulated cutting path and cutting dynamics with use of CAD/CAM to obtain machining parameters. When the materials and structure dynamics were known, cutting forces were computed and used to predict the possibility of occurrence of cutter breakage.

The dynamic status of a system or process can be monitored through analyzing the operation signals of the system. Signals collected from operation can be divided into two categories: steady signals and transient dynamic signals. The steady signals usually represent stable operation or the operation phenomenon has been running for a long period. The transient dynamic signals reflect the variation of a system encountering operation condition changes, external impact, or abnormalities. Since both types of signals display different characteristics, different signal processing method should be used for different machining abnormalities.

Fourier transform is a useful and well-known tool for signal processing. It provides the ability to understand the dynamic characteristics of a system through viewing transformed signals in the frequency domain. However, Fourier transform is not able to detect the transient change in signals, because the energy distribution of impulse signal is uniform in the frequency domain. Wavelet transform is able to detect the transient changes in dynamic signals. Adham[6] used discrete wavelet transform in smoothing kinematic data. Ho et al.[7] compressed ultraviolet-visible spectra through bi-orthogonal wavelet transform.

Many researchers studied the diagnostic system. Du et al.[8] measured force signals and obtained the characteristic values in the time domain including the ratio of cutting force range to time interval, ratio of force range to mean value of cutting force, and the characteristic values in frequency domain including peak value, frequency of peak value, and bank energy. Finally, an expert system using analysis of the characteristic values to distinguish chatter, tool wear, tool break, noise, or normal operation was produced. Shetty et al.[9] examined the role of vibration monitoring in machine tool operations and proposed a monitoring method and the associated instrument using mechatronics technology with embedded measurement design. Ahmed et al.[10] proposed a method that incorporates the features of Magneto-Rheological fluid which utilizes the input current as source to modify the magnetic field to enhance the variable stiffness and produce damping effect to control the end mill cutter vibration and suppress the chatter.

Lee et al.[11] proposed a method using feed drive AC motor current as the monitoring signals to real-time detect tool breakage. Through modeling of the feed driving system and calibration with a dynamometer, it showed that the sensitivity of the feed drive motor current is sufficient to characterize the tool breakage. Li et al.[12] also used permutation entropy of feed-motor current signals in end milling as monitoring signals to detect tool breakage. The detection method composed of estimation of entropy and wavelet-based de-nosing. Commercial tool monitoring system, such as TECHNA-CHECK Tool Monitoring Systems, also uses spindle power as the monitoring signals to monitor broken, worn and missing tools. Baek et al.[13] proposed a method using a signal processor with autoregressive (AR) model and a band energy method to extract the features of tool states to detect tool breakage and chipping in real time. The method obtained characteristic values of milling force as bank energy through the band pass filter, and diagnosed them for judging operation status through neural network analysis. Experimental results showed that AR-based method gives more accurate monitoring result.

Driver current monitoring could be a cheaper method, because it could be a sensorless approach by directly measuring the control current of the servo driver. However, the challenge of improving detection efficiency based on motor current is the tool condition hidden in the motor current signals and the current signals could also contain undesired information, such as high-frequency noise, current control errors, and driving component effects. Besides, due to the limited resolution of the spindle power signals, it is usually difficult to detect the abnormality (such as BUE or tool wear) at early stage where the variation of spindle power signals is not evident enough for monitoring. Many researches or commercial monitoring system were designed for tool breakage, worn or missing, but still not too many for build-up-edge.

Most of the developed diagnosis methods for tool state monitoring using complex signal processing algorithms require more computation time. It is not able to early detect the abnormality quickly and prevent the damages caused by the abnormality. On the other hand, if instant information of machining status, such as instant cutting locations, true spindle speed, and feedrate etc. can be extracted directly from the CNC controller as diagnosis references, the reliability of diagnosis can be further enhanced. In this study, a new on-line diagnosis and control method adopting short-time signal variation analysis and Fast Fourier Transform that can detect the BUE at its early formation duration was developed. For cutter breakage detection, in addition to short-time signal variation analysis, instant NC codes from CNC controller were directly extracted through a bi-lateral communication module and used as a machining status reference to avoid fail diagnosis. Without complex computation, the proposed system can detect the occurrence of BUE and cutter breakage at early formation duration.

Adopting Fanuc Open CNC Api Spec and Ethernet protocol, a bi-lateral communication module providing access of directly extracting information of machining status and submitting control commands from/to CNC controller to control BUE and cutter breakage without additional communication devices or cables was developed. It is more convenient for industry application. The communication module also provides the capability of recording the instant machining parameters with the diagnosis results for machining process optimization. Furthermore, a friendly communication interface using TCP/IP protocol was built so that the central monitoring platform can remote log into the on-site monitoring computer for remote operating the diagnosis/control system.

2. Diagnosis and Control Algorithm for BUE and Cutter Breakage

Experiments were conducted to on-line collect lots of vibration signals to analyze the characteristics of the build-up-edge and cutter breakage signals to develop the diagnosis algorithm. According to the characteristics of the signals, Fast Fourier Transform and short-time signal variation analysis were adopted to diagnose the occurrence of build-up-edge and cutter breakage. To avoid fail diagnosis, a bi-lateral communication module which followed Fanuc Open CNC Api Spec and Ethernet protocol and was written in C#, was developed to extract the instant machining parameters, such as spindle speed, federate, and instantly executed NC code from CNC controller for diagnosis. The

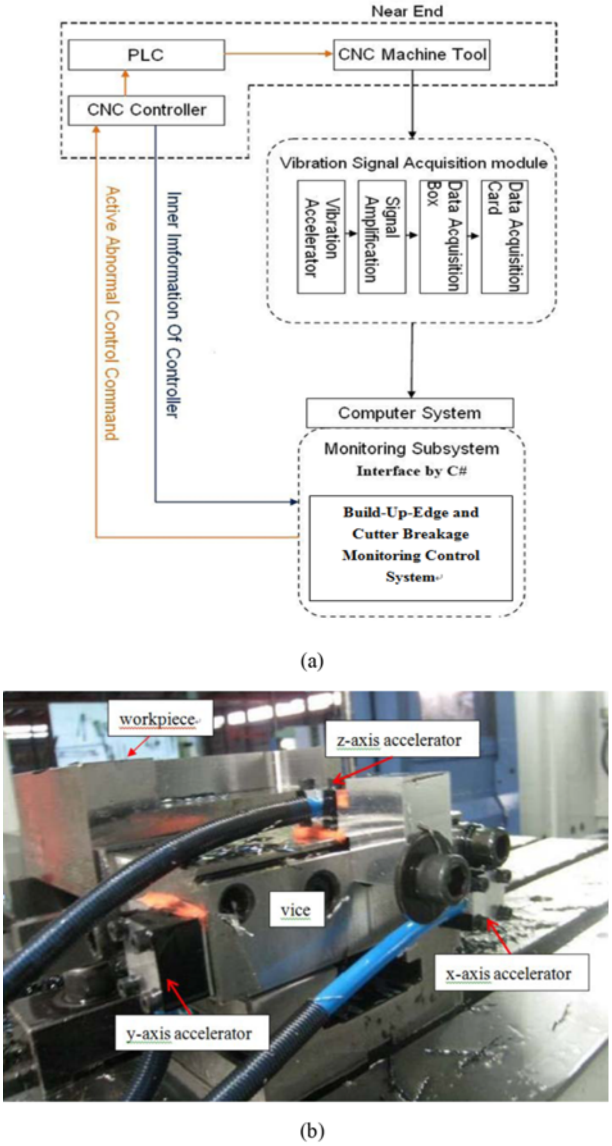


Fig. 1 Structure of the diagnosis and control system

instantly executed NC code gives the real-time cutting path information that excludes the influence of vibration caused by non-machining reason. As the BUE and cutter breakage detected, the proposed system automatically send commands to CNC controller to stop the machine for cutter replacement. Fig. 1(a) shows the structure of the diagnosis and control system, and Fig. 1(b) shows the setup of 3 accelerometers for on-line collecting the cutting vibration signals for monitoring. The accelerometers were attached on the vice where is close to the workpiece to collect the actual cutting vibration signals.

2.1 Build-up-edge diagnosis and control algorithm

According to the characteristics analysis, the vibration signal of BUE exhibits the following characteristics.

2.1.1 Characteristics of BUE vibration

(i) Sudden increase of BUE vibration

When BUE occurs, edges of cutter start losing their machining capability and machining resistance increases that causes cutting vibration increase. As it can be seen from Fig. 2, the vibration increased almost 2 times during the formation period of BUE (between the 16th and 17th second). The cutter lost most of the cutting capability after the 18th second.

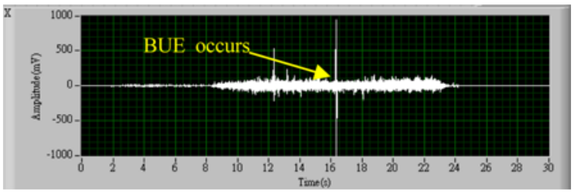


Fig. 2 Vibration signals of a milling process with BUE

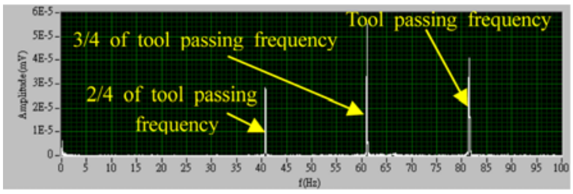


Fig. 3 Spectra analysis of the milling vibration with BUE

(ii) Frequency change of BUE vibration

When the chips melt and stick on cutter edges, the cutter edge loses its cutting capability. As a cutter edge has serious BUE, it may not have real cutting but impact and squeezing. It causes different cutting forces at the cutter edge, and the dominant cutting vibration frequencies will be influenced by the tool passing frequency of cutting vibration which changes following Eq. (1).

$$\text{Dominant vibration frequency} \quad f = \frac{S}{60} \times N \times \frac{(N-A)}{N} \qquad (1)$$

where S is spindle speed, N is number of cutting edges, and A is the number of cutting edges with BUE ($A<N$)

Fig. 3 shows the spectra analysis of a cutting process with 4-flute end mill and 1200 rpm. Because the number of cutter edges with BUE increases from 1 to 3, the dominant vibration frequencies 40 Hz and 60 Hz that are 3/4 and 1/2 of the tool passing frequency (80 Hz).

2.1.2 Diagnosis algorithm

According to the above characteristics analysis, the diagnosis algorithm for BUE is as follows:

(i) Short-time signal variation analysis

The experimental results showed that the formation of BUE took 3 seconds or less (shown as Fig. 4) During the 0-1st second it was normal cutting. BUE started forming during the 1st-2nd second, and the cutting vibration increased almost 2 times. During the 2nd-3rd second, the cutter lost it cutting capability and low-frequency vibration showed up. Thus, the first diagnosis rule is on-line taking 3-second-long vibration signals and checking the increase rate of the signals. To have conservative diagnosis, the threshold value of increase rate was defined as 1.5.

(ii) The second diagnosis rule is to check whether the dominant frequency of the collected vibration signals is changed as Eq. (1). Fast Fourier Transform analysis will be applied to on-line analyze the

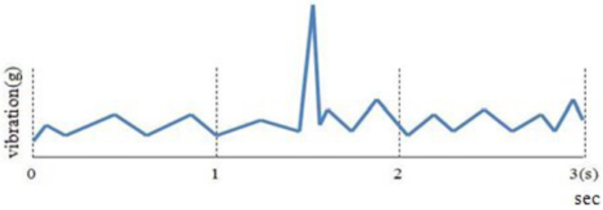


Fig. 4 Characteristics of cutting vibration with BUE

collected signals. Because the number of cutting edges is known and the true spindle speed can be directly extracted from CNC controller through the bi-lateral communication module, the tool passing frequency can be calculated for diagnosis. The associated frequencies for different number of cutter edges having BUE are calculated in advance for diagnosis.

If the above two rules are simultaneously satisfied, the warning message will be issued and the BUE control unit will be activated. In addition, when BUE exists, the dominant vibration frequencies are lower than the tool passing frequency. To minimize the influence of high-frequency noise and the resonance caused by the cutting forces, the signal filter was added to screen the signals with frequency higher than 1.1 times of tool passing frequency.

2.1.3 Control algorithm

Because a cutter damaged by BUE cannot be used anymore and machining with the cutter could damage workpiece badly, the machine tool should be stopped immediately when BUE is detected. Thus, a control command will be directly sent to the CNC controller through the bi-lateral communication module to stop the machine.

2.2 Cutter breakage diagnosis and controlalgorithm

2.2.1 Characteristics of cutter breakage vibration

Cutter breakage is mainly caused by inappropriate cutting parameters, collision, or limit of cutter life. When cutter breakage happens, no machining is conducted. To minimize the invalid of machining time, machine tool should be stopped for cutter replacement as early as possible, when cutter breaks during machining.

Fig. 6 shows the characteristics of the cutting vibration of a milling process with occurrence of cutter breakage. The cutting vibration will suddenly increase due to breakage impact and quickly drop to almost zero due to disappearance of cutting force. At this moment, the existed vibration is mainly from the spindle free rotation and machine movement without cutting. The vibration was gradually decreased to almost zero (only took 0.26 seconds). Fig. 7 shows the change of vibration when cutter breakage happens. As it can be seen from the figure, the vibration dropped to near zero at the 20th second within 0.01 second. According to lots of experimental data, it was found that the ratio of the vibrations before breakage to the vibration after breakage is 3 or up.

2.2.2 Diagnosis algorithm

When cutter breakage happens, the vibration will have two characteristics: (1) vibration jumps within 0.01 second and immediately drops to near zero after jump; (2) ratio of increased vibration to dropped vibration is 3 or up.

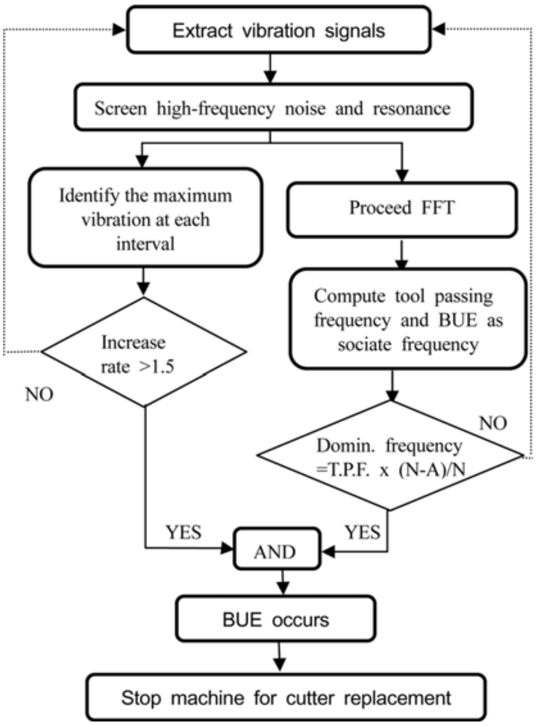


Fig. 5 Flowchart of the diagnosis and control process for BUE

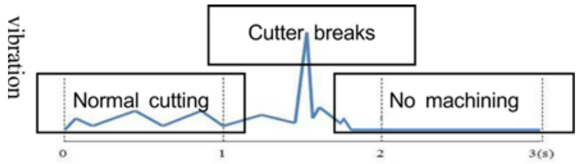


Fig. 6 Characteristics of cutter breakage vibration

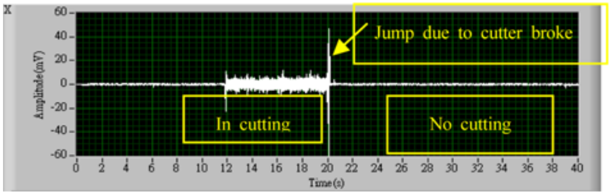


Fig. 7 Machining vibration with cutter breakage

According to the two characteristics, 0.5-seconds-long vibration signals is extracted and divided into N segments each time for diagnosis. The root-mean-square (r.m.s.) value of each interval vibration is computed, and the ratio of the nth segment vibration to the (n+2)th segment vibration is computed. Two rules are then checked for diagnosis: (1) whether the ratio of vibration comparison is 3 or up; (2) whether the magnitude of vibration at the (n+2)th segment is close to the value caused by spindle running rotation and machine movement without cutting. If the two rules are satisfied, warning message will be issued and the control unit will be activated.

Before monitoring, the system will pre-measure the machine vibration under the condition that spindle is free running without cutting for 10 seconds and calculate the average value of the maximum vibrations at divided intervals. The value is regarded as the threshold and then saved to the monitoring system for diagnosis.

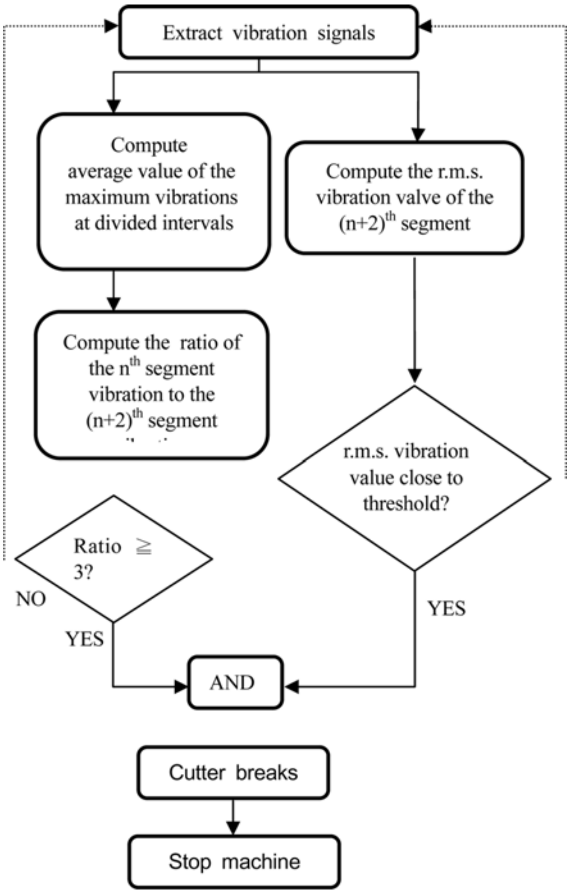


Fig. 8 Flowchart of the diagnosis and control process

To prevent fail diagnosis, the instantly executing NC code is directly extracted from CNC controller through the developed bi-lateral communication module during diagnosis process, to ensure that the detected vibration changes is not due to the normal change of cutting path.

2.2.3 Control algorithm

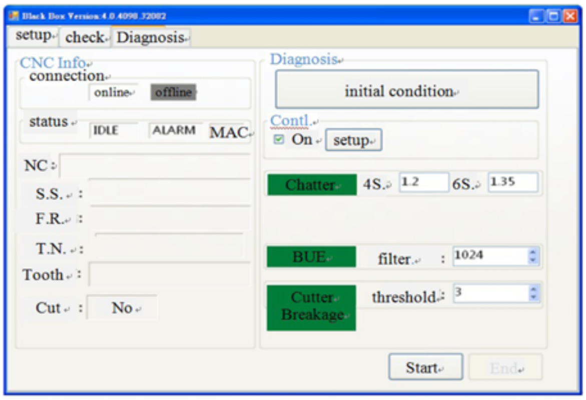
When cutter breaks, the machine tool should be stopped as soon as possible to minimize the invalid machining time and replace cutter. Thus, the monitoring system will directly send machine-stop command to the CNC controller through the bi-lateral communication module, when cutter breakage is detected.

Fig. 8 shows the diagnosis and control flowchart for cutter breakage.

3. On-Line Monitoring and Control System

Based on the proposed diagnosis and control algorithms, an on-line chatter monitoring and control system was written in C#. The system was installed in an on-site computer and can directly communicate with the CNC controller. Accelerometers were used to on-line collect the vibration signals. Fig. 9 shows the interface of the system.

To avoid fail diagnosis, a bi-lateral communication module that can call the Application Programming Interface (API) to extract instantly executed NC codes, true spindle speed and feedrate was developed based on Fanuc Open CNC Api Spec and Ethernet protocol for on-line verifying the current machining status for diagnosis reference. The module can also extract other instant machining information and control parameters from the CNC controller and upload them with the diagnosis/control results to the remote central monitoring platform. The information can be used for machining process optimization in the future.



☑ On

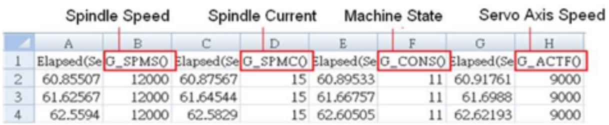
Cut : No

4S. 1.2 6S. 1.35

filter : 1024

threshold : 3

Fig. 9 The interface of the diagnosis and control system



	A	B	C	D	E	F	G	H
1	Elapsed(Se	G_SPMS()	Elapsed(Se	G_SPMC()	Elapsed(Se	G_CONS()	Elapsed(Se	G_ACTF()
2	60.85507	12000	60.87567	15	60.89533	11	60.91761	9000
3	61.62567	12000	61.64544	15	61.66757	11	61.6988	9000
4	62.5594	12000	62.5829	15	62.60505	11	62.62193	9000

Fig. 10 The extracted machining information shown on the central remote monitoring platform

Fig. 10 shows the extracted instant information shown on the central remote platform. When abnormality is detected, the module can communicate with the PLC (Programmable Logic Controller) of the CNC controller to transmit chatter control commands to the CNC controller for fast suppression.

With Ethernet protocol, the system also provides the function that the remote central monitoring platform can remote log into the on-site diagnosis/control system. For real time monitoring, if the priority of TCP/IP is not high, there can be a transmission delay of abnormality signal and the efficiency of real-time monitoring is influenced.

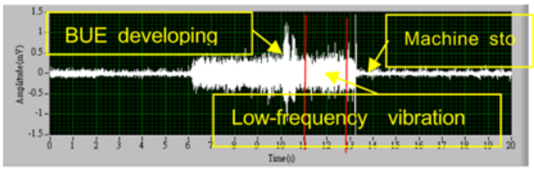
4. Experimental Verification

BUE monitoring experiment and cutter monitoring experiment were conducted to verify the proposed diagnosis and control algorithms and the effectiveness and feasibility of the developed system.

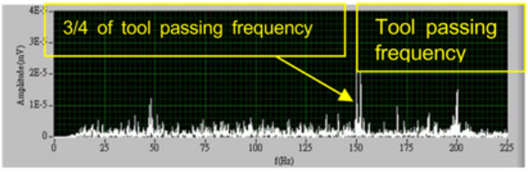
In the BUE monitoring experiment, a 4-flute tungsten carbide end mill with diameter of 12 mm was used to cut Al6061. Straight line cutting path was planned. The cutting parameters were shown in Table 1. Accelerometers with data acquisition card (DAQ card) were used to on-line extract vibration signals for diagnosis. Fig. 11 shows the vibration signals and spectra analysis of the experiment. BUE developed during the 10~11th second. The vibration had a sudden increase when BUE formed. The vibration occurred after 11th second exhibited low-frequency characteristics. According to the result of FFT, it was noted

Table 1 Conditions of BUE monitoring experiment

Cutting tool	Ø12 × 4-flute (tungsten steel tool)
Workpiece material	A6061 T6
Cutting path	Straight line
axial depth of cut (mm)	4
radial depth of cut (mm)	12
Spindle speed (rpm)	3000
Feed drive (mm/min)	450
Cutting passing frequency (Hz)	200

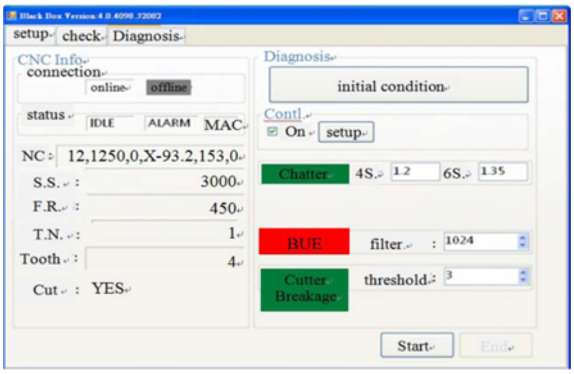


(a) Vibration signals in time domain



(b) Spectra analysis with FFT

Fig. 11 Vibration signals and Spectra analysis for BUE experiment



connection: online offline

status: IDLE ALARM MAC

☑ On

NC : 12,1250,0,X-93.2,153,0

S.S. : 3000

F.R. : 450

T.N. : 1

Tooth : 4

Cut : YES

4S. 1.2 6S. 1.35

filter : 1024

threshold : 3

Fig. 12 Interface of the system with BUE alarm showed

that one of the dominant vibration frequency is 150 Hz which is 3/4 of the tool passing frequency 200 Hz. Since the diagnosis rules were matched, the system showed alarm (Fig. 12) and stop the machine for cutter replacement. The total monitoring time was about 3 seconds. Fig. 12 was the interface of the proposed system. Fig. 13 showed the cutter with BUE.

In the cutter breakage monitoring experiment, a 2-flute tungsten carbide end mill with diameter of 12 mm was used to cut Al6061. Straight line cutting path was planned. The cutting parameters were shown in Table 2. In the experiment, the cutting was continuously repeated until the cutter broke. After many cuttings, the cutter wore and finally broke. Fig. 14 showed the vibration signals of the machining process. It was noted that cutter broke during 16~17th second, and the vibration had a significant increase and then quickly dropped to a very small value. As it can be seen from the figure, the system detected the occurrence of cutter breakage and stopped the machine within 1

Fig. 13 The cutter with BUE

Table 2 Conditions of cutter breakage monitoring experiment

Cutting tool	Ø12 × 2 -flute. (tungsten steel tool)
Workpiece material	A6061 T6
Cutting path	Straight line
axial depth of cut (mm)	4
radial depth of cut (mm)	8
Spindle speed (rpm)	3000
Feed drive (mm/min)	750

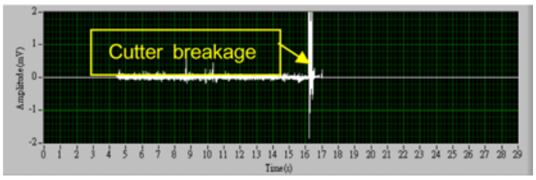
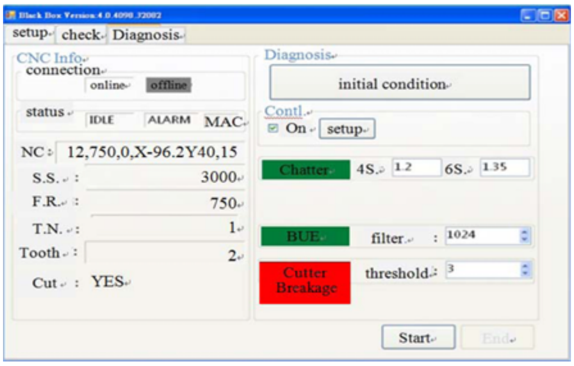


Fig. 14 Vibration signals of cutter breakage experiment

Fig. 15 Photo of the broken cutter



connection: online offline

status: IDLE ALARM MAC

☑ On

NC : 12,750,0,X-96.2Y40,15

S.S. : 3000

F.R. : 750

T.N. : 1

Tooth : 2

Cut : YES

4S. 1.2 6S. 1.35

filter : 1024

threshold : 3

Fig. 16 Interface of the system with cutter breakage alarm showed second. It shows the effectiveness of the proposed system. Figs. 15 and 16 respectively showed the broken cutter and interface of the system with cutter breakage alarm showed.

5. Conclusions

An on-line diagnosis and control method with use of Fast Fourier Transform and algorithm of short-time signal variation analysis algorithm was developed for BUE and cutter breakage in this study. In addition, a bi-lateral communication module providing the capability to directly extracted information and send control commend from/to the CNC controller was developed for diagnosis. Based on the proposed method and use of TCP/IP communication protocol, an on-line diagnosis and control system with characteristics of high computation efficiency, friendly communication, and remote log-in capability was also built. Verification experiments were conducted to verify the effectiveness and feasibility of the proposed system. Experimental results showed that the system can complete the diagnosis and control of BUE within 3 seconds and complete the diagnosis and control of cutter breakage within 1 second.

ACKNOWLEDGEMENT

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