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절삭공구의 채터진동과 음향방출과의 실험적 연구

이 종 길*

Experimental Analysis of Chatter Vibration and Acoustic Emission of Cutting Tool

Jong kil Lee*

ABSTRACT

본 연구에서는 절삭공구가 채터진동을 일으킬때 AE(Acoustic Emission) 신호와 어떤관계가 있는지를 실험적으로 연구하였다. 모달분석을 통하여 절삭공구의 고유진동수 및 모우드형상을 구하였으며, 실제 절삭실험에서는 이송방향 및 절삭방향의 가속도를 계측하여 위상차를 결정하였다. AE신호와 두 가속도와의 관계를 알기위하여 AE 실험을 하였다. AE신호의 폭발점은 대개 Lissajous loop의 방향전환점에서 관찰되었다.

Key Words : Chatter Vibration, Acoustic Emission, Experimental Modal Analysis, Cutting Tool, Frequency Spectrum, Lissajous Loop, AE Burst Events

1. INTRODUCTION

There are many sources of excitations that cause machines and structures to vibrate. In the operation of metal cutting, cutting tool energetic vibrations are often encountered. Vibrations of the cutting tool-workpiece are also common in machining processes. There are two types of dynamic phenomena that cause such vibrations: (a) externally excited oscillations which is caused by shock (or impulsive) loading of the cutting tool (e.g. when the tool suddenly enters the workpiece or strikes a hard grain in the workpiece) or by such periodic excitations as unbalanced rotation elements, mounting defects, bearing imperfections or misalignments in machine components, and (b) cutting tool chatter which is a "self-excited" oscillation[1,2].

How is chatter defined? By strict definition, chatter occurs when the relative tool-work displacement is such that cutting is briefly interrupted, for instance by the chip thickness going to zero as the tool leaves the cut. Regenerative chatter is "self-excited" oscillation. Other types of chatter exist, for instance non-sustaining chatter of intermittent cutting operations such as face milling, which is not self-excited, but is not regenerative.

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* 국방과학연구소

It is this final type of chatter that we are observing here.

An extensive research effort has been focused on chatter vibration of lathe tools[3-8]. Tobias[8] and Tlusty[1] proposed the regeneration phenomenon and the mode coupling effect as the two most important causes of chatter mechanisms. Recently, vibration monitoring of machining was well reviewed by Lee et al[10]. They summarized the key points of various published reports and discussed the critical technical issues which are hindering transformation of the laboratory results to more broadly applicable technology.

This research was initiated as part of an effort to resolve questions concerning tool wear monitoring using acoustic emission and tool vibrations during metal cutting. Both chatter and cutting tool wear monitoring are important research subjects. However, the objective of this research was to determine how the cutting tool vibrates when chatter occurs and how this motion is related to acoustic emission. All tests were conducted in Monarch 20″ CM lathe and the Cutting Tool Support Structure(CTSS) system is shown in Fig. 1.

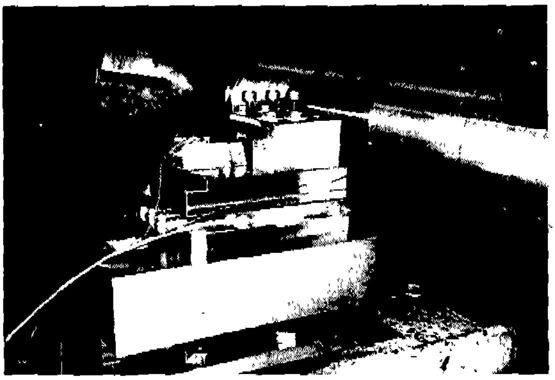

Fig. 1 Photograph of the CTSS system

2. EXPERIMENTAL SET-UP

2.1 Modal Analysis Impact Test

Modal analysis is a popular experimental procedure for identification of resonant frequencies and mode shapes. The transfer function method is the modal analysis technique that was used to obtain the results presented in this paper. Several researchers[11-13] studied modal analysis of machine tool structures. Eman et al.[11] proposed a new approach for modal analysis of machine tool structures based on experimental data. Shin et al.[12] presented a detailed procedure for experimental complex modal analysis of a machine tool structure by Dynamic Data System method.

Actually, the frequency response function measurements of the CTSS system contain random noise. To eliminate thes noise and find accurate modes, a mode indicator function which is a composite spectrum that accentuates modal peaks was used in the actual modal impact tests. To find the two dimensional, X-Z plane (feed and cutting directions plane), mode shapes of the CTSS system, two frequency response measurements at each test point were acquired. A commercially available software package was used to perform the mathematical manipulations which reduced the measured sets of transfer functions and generated plots of the mode shapes and tables of the natural frequencies and damping values.

The CTSS system is composed of four parts as shown in Fig. 2: base block, dynamometer, cutting tool and tool support. It is assumed that the base bolck is completely fixed on the body of the lathe. The tool support is mounted on the dynamometer by four bolts. Because of these four bolts, it is difficult to measure the frequency response at the exact node points. A schematic of the equipment for modal analysis is shown in Fig. 3.

2.2 Two Dimensional Cutting Test

To determine the phase relation between the accelerations in the feed direction(a_z) and cutting direction(a_x), dry turning operations were carried out on a AISI 1018 steel cylindrical workpiece.

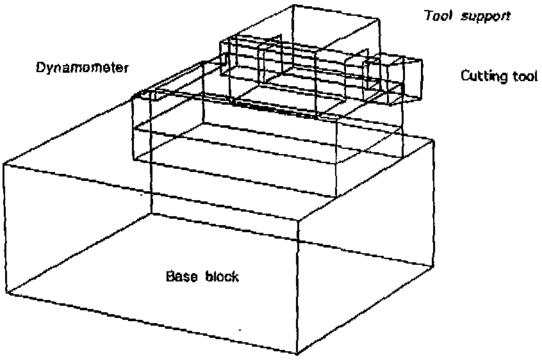

Fig. 2 Model of the CTSS system

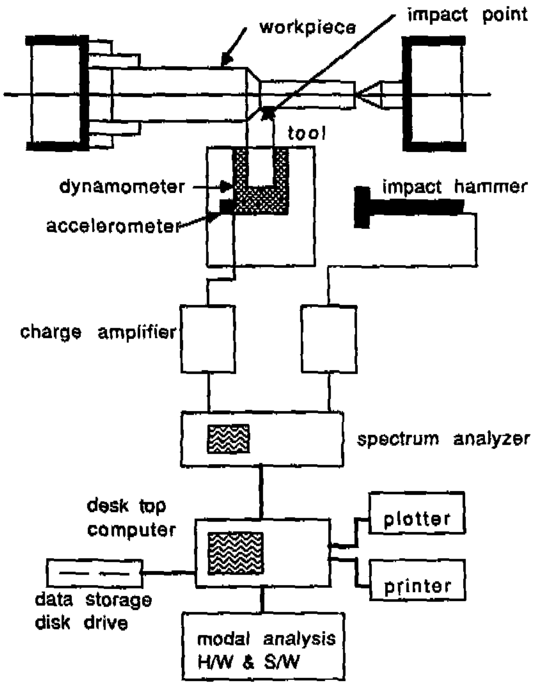

Fig. 3 Schematic of modal test equipment

Force components acting on a cutting tool in turning and geometric coordinate are shown in Fig. 4. The workpiece was 12.54 cm in diameter and 91.44cm in length, originally. The runs were made on a of Monarch 20"CM lathe and the experiments were limited to a single type of tool and a single workpiede. The tool was type FN11R-44A and the tool tip was cemented carbide. The experimental setup is shown in Fig. 5. The two accelerometers located in the feed and cutting directions were PCB models 302A07 and 303A03 as shown in Fig. 5, respectively. Cutting conditions were carefully chosen so as to obtain chatter vibration. Experimental conditions for cutting tests are shown in Table 1. The rotational speed, feed rate and depth of cutting have been kept constant.

If chatter vibration occurs, signals output by both of the accelerometers are amplified by separate power amplifiers. In order to eliminate high frequency noise components and to get more accurate estimations a two channel low pass filter was used. The typical cut-off frequency for the low pass filtering was 5 kHz.

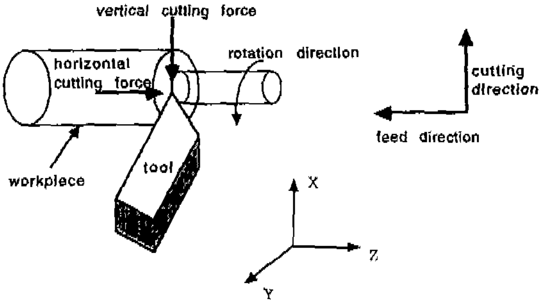

Fig. 4 Force components in turning

2.3 Acoustic Emission Test

Acoustic emission tests were performed to know the relation between acoustic signals and two accelerations(feed and cutting direction). In previous research, acoustic emission(AE) analysis, has been proven effective as a sensing methodology for monitoring of tool conditions(14-15). AE can be monitored simply by mounting a sensor(transducer) on the tool holder or tool itself. The frequency of AE

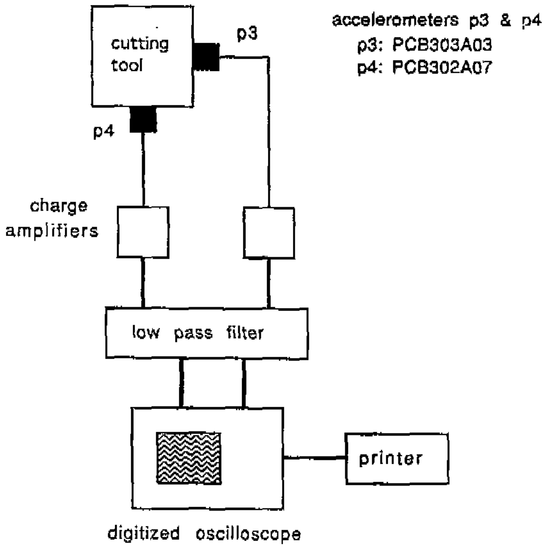

Fig. 5 Schematic of cutting test equipment

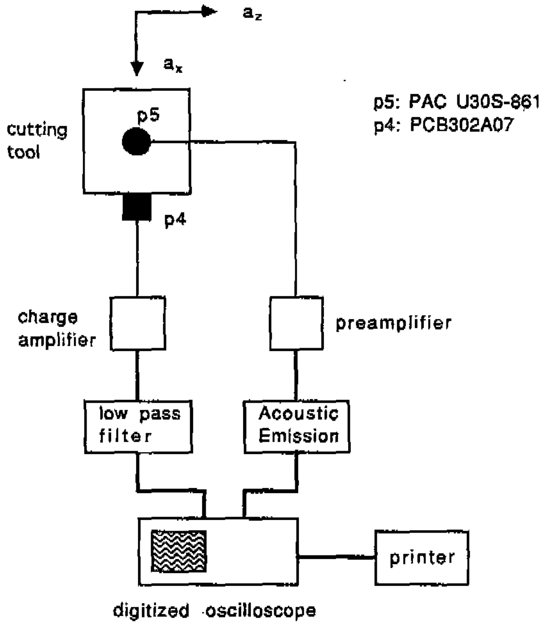

Fig. 6 Schematic of AE test

signal is typically in the range of 100 kHz to 1 MHz which means that the frequency range of the AE signal is much higher than that of the machine vibrations and environmental noises. Most of the published studies of the AE have concentrated primarily on the turning of metals.

In recent years many researchers have investigated AE signals from metal cutting process. AE can originate from five different sources in metal cutting: (a) material deformation in the shear zone during chip formation, (b) chip motion, sliding and sticking, (c) chip breaking or fracture, (d) impact of broken chips on tool or workpiece, (e) tool-workpiece rubbing, friction[14-15].

To determine the relation between AE and the two accelerations, feed and cutting direction accelerations, the equipment was set up as shown in Fig. 6. The AE sensor, PAC model U30S-861, was attached to the rear face of the tool with a screw clamping mechanism. If chatter occurs, the output AE signal is amplifed by a preamplifier and fed into a main amplifier. The output acceleration signal is amplified by a charge amplifier and fed into the low pass filter to eliminate high frequency components. The typical cut-off frequency for low pass filtering was 5 kHz. Cutting conditions were carefully chosen so as to obtain chatter vibration. Experimental conditions for AE tests are shown in Table 1.

Table 1 Cutting Tests Conditions

Cutting Conditions	Data
Cutting speed	400 rpm
Feed rate	0.009652 mm/rev
Depth of cut	0.508 mm

3. RESULTS AND DISCUSSION

Modal analysis impact tests were conducted to obtain the natural frequencies and mode shapes of the cutting tool support structures (CTSS). The

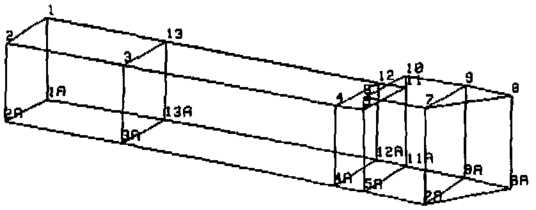

Fig. 7 Undeformed structure of cutting tool

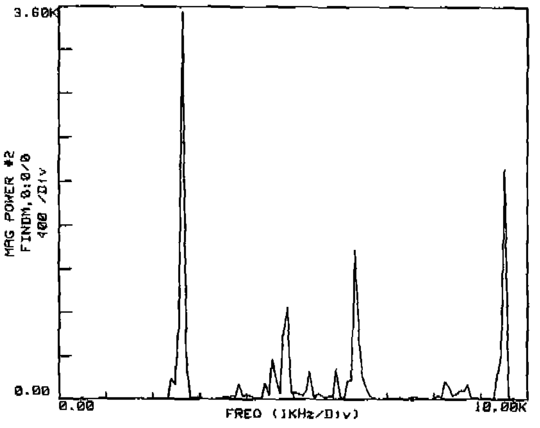

Fig. 8 Mode indicator function of cutting tool

Table 2 Modal parameters for the cutting tool

Mode no.	Frequency	Damping
1	2626 Hz	0.185 % (4.9 Hz)
2	4721 Hz	0.413 % (19.5 Hz)

dynamometer is mounted on the base bolck of the CTSS and the tool is fixed on the platform by a tool support. The base plate has mounting flanges with slots to take 8 mm fixing bolts. Actually, cutting tool structures are continuous systems with an infinite number of degree of freedom and, hence, an infinite number of natural frequencies and modes. However, from a practical point of view a certain frequency range is of importance for analysis. The model of the cutting tool undeformed structure, with 24 node points is shown in Fig. 7. Fig. 8 shows the result of the mode indicator function. It is clear that the natural frequencies of the cutting tool are 2640 Hz, 4700 Hz, 6320 Hz and 9520 Hz, etc.. The modal parameters for the first two modes of the cutting tool are shown in Table 2. The damping "%" and "Hz" values represent the damping ratio $\zeta = c/c_{critical}$. Two dimensional animated mode shapes were produced for the frequency of 2626 Hz, mode 1, and 4721 Hz, mode 2. Fig. 9 shows the mode shape of the cutting tool mode 1, at the frequency of 2626 Hz.

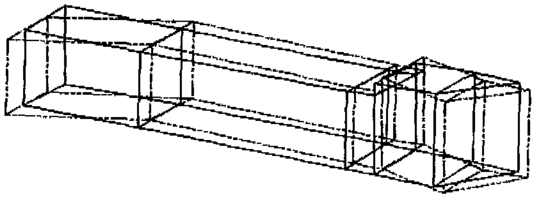

Fig. 9 Mode shape of cutting tool at 2626 Hz

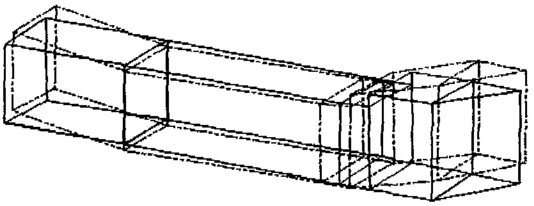

Fig. 10 Mode shape of cutting tool at 4721 Hz

Fig. 10 shows that animated mode shape of the tool at the freqeuncy of 4721 Hz, mode 1. Fig. 11 shows the Y-view of the tool edge (viewing the tool edge in the direction away the workpiece). It can be seen that the trace of the tool edge motion is an ellipse in the feed and cutting directions plane and the rotation direction of the tool edge is counter-clockwise around the ellipse. Therefore, it can be assumed that the motions in the X and Z directions are both sinusoidal but of different amplitudes and phases. This leads *theoretically to* the tool edge moving on exactly an elliptical path in X-Z plane. Experimentally this is found to be approximately true. Fig. 12 and 13 show the two dimensional animated mode shapes of the CTSS

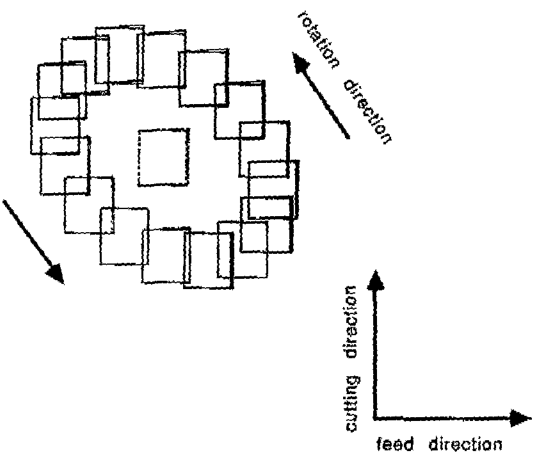

Fig. 11 Y-view and trace of the tool edge at 4721 Hz

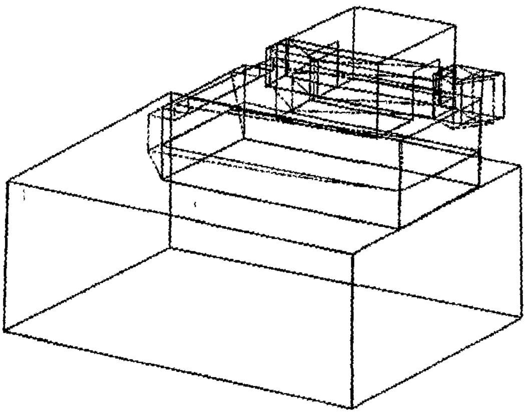

Fig. 12 Mode shape of CTSS at 2686 Hz

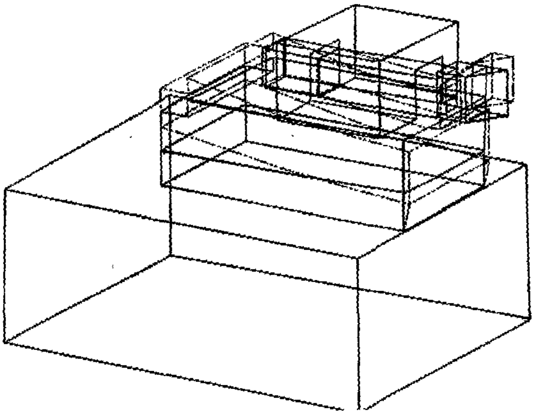

Fig. 13 Animated mode shape of CTSS system at 4917 Hz

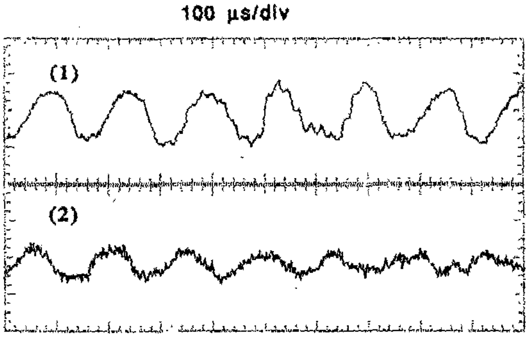

Fig. 14 Feed (1) and cutting (2) direction accelerations for regular cutting

system at the frequencies of 2686 Hz and 4917 Hz, respectively.

During a metal cutting operation, chatter is often a source of problems associated with poor surface finish, and reduced tool life and the various components of the cutting forces fluctuate rapidly. In this section, the frequency spectra and time domain traces of the feed and cutting direction accelerations of the cutting tool are discussed. To determine the phase relation mounted on the bottom and side face of the cutting tool as close as possible to the tool edge. The actual cutting process was continued until chatter was detected. Cutting conditions were carefully chosen so as to obtain chatter vibration(see Table 1). Usually, chatter is produced by a worn tool. If chatter occurs, a high frequency "beeping" sound can be heard from the tool and workpiece. Most of the energy of the noise associated with this vibration is within the audible range of frequencies. Fig. 14 shows the feed and cutting direction accelerations for regular cutting. Using these two accelerations, a Lissajous Fig. was constructed for regular cutting as shown in Fig. 15(horizontal and vertical axes are feed and cutting

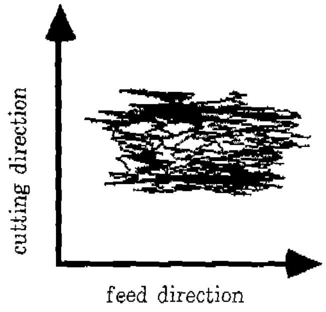

Fig. 15 Lissajous figure for regular cutting

direction accelerations, respectively). The Lissajous loop developed at the cutting conditions prior to chatter describes a chaotic type of behavior, indicating a non-linear relatonship between the feed and cutting direction accelerations. Fig. 16 shows typical traces of the accelerations for cutting with chatter. The period of both traces is 212 µs, hence, the frequency of both two modes, feed and cutting direction accelerations, is 4717 Hz. Both traces, feed and cutting diretion accelerations, appear to be continuous and simple harmonic at about 4717 Hz, which is nearly equal to one of the tool natural frequencies, 4721 Hz. It is also seen that the feed direction acceleration leads the cutting direction acceleration, i.e. the maximum feed direction acceleration occurs before the maximum cutting direction acceleration, but at a constant phase angle Ψ (obvious based on frequency response of linear system) as shown in Fig. 16. The phase angle Ψ is computed by $\Psi = 2\pi f \tau_d$ where, f (= 4717 Hz) and τ_d (= 120 µs) are frequency and delay time of the two traces, respectively. It can be easily calculated that Ψ is nearly 207 degree. Therefore, the feed direction acceleration lags the cutting direction acceleration by 153 degree (or the cutting direction acceleration leads the feed direction acceleration by 153 degree). This behavior is expected, i.e. that one mode (cutting direction 4717 Hz) will go unstable and excite the other mode (feed direction with a lower natural frequency) with a periodic excitation with a fundamental frequency of 4717 Hz. This result would be that the response of the feed direction should lag the excitation introduced by the cutting direcion, by some amount prescribed by the level of damping in the feed direction. The angle representing this phase lag is equal to $360° - \Psi$ and must be such that $0° < \Psi < 180°$ since the natural frequency of the feed direction is less than in the cutting direction.

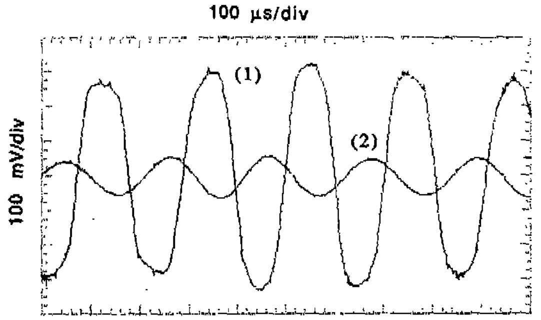

Fig. 16 Feed (1) and cutting (2) direction accelerations for chatter cutting

From the traces of the feed and cutting direction accelerations, a Lissajous Fig. was developed as shown in Fig. 17. The Lissajous loop under chatter cutting was observed always to be approximately an ellipse (horizontal and vertical axes are feed and cutting direction accelerations, respectively). From Fig. 16, if the feed direction acceleration is at its maximum value and is moving towards the negative acceleration direction, the cutting direction acceleration going from the negative direction to the positive direction. Therefore, rotation direction of the Lissajous loop is counterclockwise. This rotation direcion and motion of the tool edge is consistent with the result of the modal

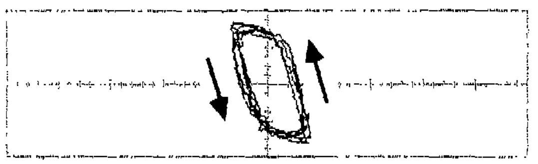

Fig. 17 Lissajous figure for chatter cutting

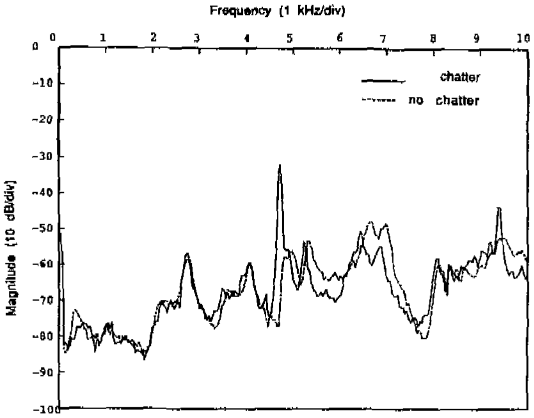

Fig. 18 Frequency spectrum for the feed direction acceleration

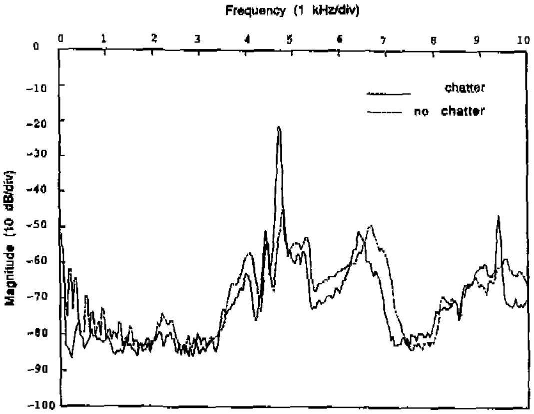

Fig. 19 Frequency spectrum for the cutting direction acceleration

analysis impact test of the cutting tool(see Fig. 11). For the general case of steady sinusoidal motion of mode coupling chatter, the motions in the feed and cutting directions are both sinusoidal but of different amplitudes. Their phase relationship is determined by the equation $\Psi=2\pi f\tau_d$. This leads theoretically to the tip of the tool moving on an elliptical path in the feed and cutting direction plane.

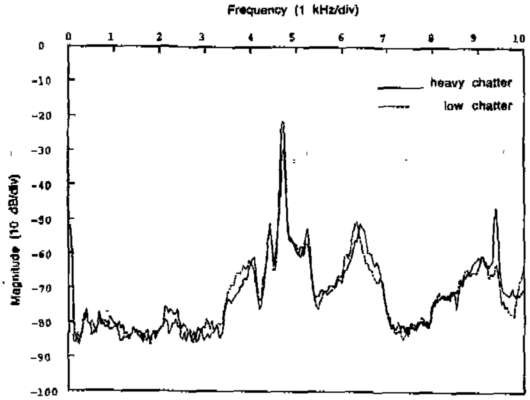

Fig. 20 Frequency spectra of low chatter vs. heavy chatter for cutting direction

To monitor the frequency spectra of the vibration signal for cutting with chatter, an accelerometer, oriented in either the feed or cutting directions, was mounted on the tail section of the tool. The output of this accelerometer, after passing through amplifiers, was fed into a spectrum analyzer. The accelerations, from both the feed and cutting directions, with chatter and with no chatter were compared as shown in Fig. 18 and 19. If chatter occurs, the accelerations at a frequency of 4700 Hz were suddenly increased as shown in Fig. 18 and 19. Cutting direction acceleration of low chatter and heavy chatter was compared as shown in Fig. 20. However, there is no clear criterion between low vhatter and heavy chatter and a subjective judgment was used. From Fig. 20, the amplitude of heavy chatter, at the frequency of 4700 Hz, was increased about 10 dB above that with low chatter.

To determine the relation between AE signal and cutting direction acceleration on metal cutting, orthogonal cutting tests were conducted under stable cutting conditions without a lubricant. The cutting conditions for AE tests are shown in Table 1. Dornfeld[14] reported that during machining, a significant amount of the AE signal generated is due to fracture of the chip formed, typically appearing as burst emissions. Fig. 21 shows the output AE signal after 135 minutes,

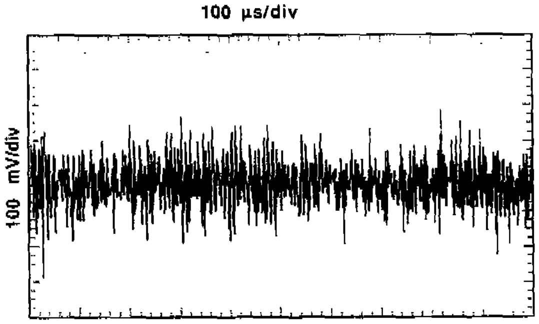

Fig. 21 AE signal after 10 minutes

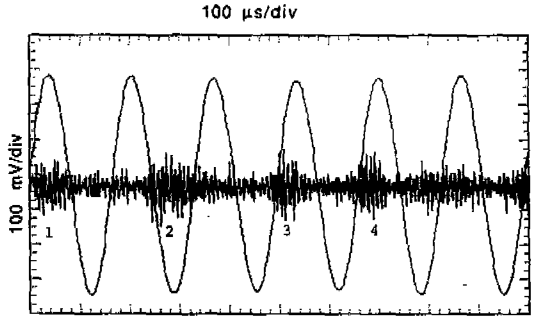

Fig. 22 AE signal and cutting direction acceleration after 200 minutes

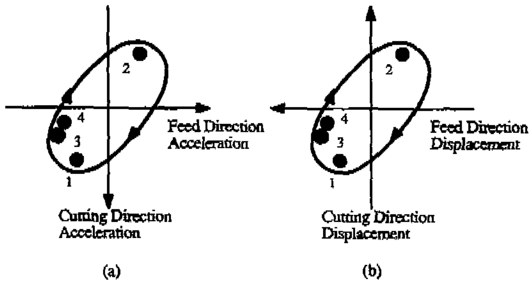

Fig. 23 Lissajous loop and AE burst events

heavy, fully developed chatter, was detected. At this time, an accelerometer was attached at the bottom of the tool. Fig. 22 shows the AE signal and cutting direction acceleration after 200 minutes from initial cutting. Several burst events can be seen in Fig. 22. In analyzing the relationship between AE signal and a Lissajous loop, the results of the Fig. 16, 17 and 22 were used. Fig. 23 is the tool tip motion as obtained from the modal analysis and chatter cutting tests(at the frequency of 4714 Hz). A view of the tool edge acceleration looking toward the workpiece is shown in part (a) of Fig. 23. Burst events #3 and #4 occurred between zero and the maximum positive cutting direction acceleration, hence the burst events of the AE signal occur at the black marked points as shown in Fig. 23. Therefore, the burst events of the AE signal for cutting with chatter occur approximately at the diretion turning points of the Lissajous Fig. in the plane of feed and cutting direction accelerations. Matsumoto, Y. et al experienced same result but it was not published[17]. Table 3 shows the relationship between displacements and velocities and accelerations of the tool motion. Displacement traces are same as the reversed acceleration traces because positive accelerations mean negative displacements with different amplitude as shown in Table 3. A view of the tool edge displacement looking toward the workpiece is shown in part(b) of Fig. 23. Burst events of the AE signals occurs at the black marked points. Therefore, the burst events of the AE signal for cutting with chatter occur approximately at the direction turning pionts of the Lissajous loop in the plane of feed and cutting direction displacements. However, this is simply an experimental obserbation. All physical actions involved in the chip-marking process are sufficiently active acoustic events that the AE signals from the cutting process can carry detailed information about the cutting tool, chip, and workpiece interactions. The AE signals from the metal cut-

Table 3 The motion for the cutting tool

Motions	Feed direction	Cutting direction
Displacement	$X\sin\omega t$	$Z\sin(\omega t+\psi)$
Velocity	$\omega X\cos\omega t$	$\omega Z\cos(\omega+\psi)$
Accelertaion	$-\omega^2 X\sin\omega t$	$-\omega^2 X\sin(\omega+\psi)$

Note;X, Z:Amplitude, ω:Natural circular frequency, and ψ: Phase angle ting processes appear as a continuous wave of very high frequency content, resulting from densely packed AE events, with occasional bursts events of higher energy. The factors which have the most influence on the AE bursts events are the strain rate of shear deformations, the yield strength of the workpieces, and the volume of the deformation zone. However, careful verification and better interpretation of the mechanism of the AE bursts events are needed before any practical system can be developed.

4. CONCLUSIONS

As mentioned previously, the objective of this research is to determine how a cutting tool vibrates when chatter occurs and how this motion is related to the acoustic emission signal. From the preceding work, the following conclusions were drawn. From the two dimension animated mode shape(experimental modal analysis) at the frequency of 4721 Hz, motion of the tool edge was elliptical and its rotation direction with respect to the feed and cutting directions was counter-clockwise around the ellipse. The actual cutting process was continued until chatter was detected. Cutting conditions were carefully chosen so as to obtain chatter vibration. However, this is no regenerative chatter, it is chatter in the cutting direction, i.e. it is not caused by regeneration-the increase and decrease in material removal due to what occured at the previous tooth pass. This is an interesting phenomenon in itself. Only the frequency of 4700Hz(one of the natural frequencies identified by modal analysis) is frequency excited by the chatter occured during the experiment. The Lissajous Fig. under chatter cutting was observed always to be approximately an ellipse with respect to feed and cutting direction accelerations. Rotation direction of the Lissajous loop was counter-clockwise. This rotation direction was consistent to the result of modal impact test. When chatter occurred, the accelerations at the frequency of 4700Hz were suddenly increased.

From AE test for cutting with chatter, there were several burst events, approximate periodically, in the AE signal. Burst events of the AE signal occurred approximately at the direction turning points of the Lissajous Fig.. However, because of the irregularity of chip formation(continuous and discontinuous) and chip-breaking frequency during chatter cutting, in real time applications, it is difficult to analyze the output AE signal. Careful verification and better interpretation of the source mechanism of the AE bursts events are needed before any practical system can be developed. However, the chatter vibration and AE burst signals from this metal cutting processes contain some useful information. To solve some of the existing questions concerning tool wear in metal cutting, this research will lead to more understanding it.

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