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Cutting stability investigation on a complicated free surface machining

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Analysis and modelling

ABSTRACT

Purpose: Both the results obtained previously relating to structure dynamics of a simultaneous five-axis movement machine tool and to the investigations on dynamic cutting behavior are further applied as a foundation to study the effect of the process parameters on the cutting stability in the process of a complicated free surface machining.

Design/methodology/approach: In the paper cutting stability investigation on a complicated fee surface machining are described.

Findings: The experimental data obtained from the cases with and without a real cutting process find that a test under a specified rotational speed can generate its own charcteristic 3-direction frequencies. The paper specially select the characteristic frequency with the most significant change on response amplitude to analyze.

Practical implications: The investigation procedures and the results obtained may be used as a reference and guidance for the analysis of cutting stability in the five-axis machining of a complicated surface in industrially practical use.

Originality/value: The results shown on frequency domain for identifying characteristic frequencies can be interpreted on time domain to observe amplitude variation respect to time and further understand its changing pattern under the cutting process.

Keywords: Five-axis machining; Frequency response; Vibration modes; Cutting stability; Spectrum analysis

1. Introduction

Industry has been constantly pursuing a desirable cutting performance of high precision, fast productivity as well as less maintenance. Conventionally, a three-axis machine tool is widely used to achieve a machining process on a workpiece. However, as for complicated surface, its lack of five-axis freedom, that is required to ensure a secured range of collision-free distance between tools and workpieces, results in an undesirable performance either on precision or on processed surfaces. This is frequently amended by adopting massive post processing. Sometimes, the resulting precision and efficiency can not fulfill the requirement of industry. Therefore, a five-axis rather than three-axis machine tool is now favorably used to seek for higher precision and faster productivity. Under this trend, the vibration problem associated with annoying noise in processing may become more serious especially on quality, precision, tool life, machine usage, and cutting efficiency. Furthermore, the aggravating tool wear may result in cutting tool fracture and machine tool itself damage. Hence, analyzing the resulting vibration generated from a machining process can extend the application of experimental know-how of dynamic cutting to this area, and may be beneficial to design of process parameters and planning of a cutting process.

As stated above, it is now clear that the vibration phenomenon in cutting processes has large impact on surface roughness, smoothness, and dimension accuracy of workpiece, as well as tool life and machine. The emitted high-frequency noise can further cause environmental pollution and also low production rate. Thus, vibration has been a major issue in studying the cutting processing of machine tool. However, it is still far beyond fully understanding since its behavior and characteristics is too complicated to build up an accurate model for analyzing. In the cutting processes of machine tools, vibration can be classified as four types based on source and type of exciting force:

1. Forced vibration by impact – caused by the impact between tools and workpieces due to the existing material non-uniformity, such as granules and porous apertures, of the cut workpiece as the cutting process starts. This can be gradually dissipated owing to damping of mechanical structure.
2. Forced vibration from sources other than cutting processes – generated by the periodical excitation from the unbalanced rotation of the machine components.
3. Forced vibration from cutting processes – induced by cutting discontinuity and accumulation of chip. This type of vibration is closely related to cutting situation, but is not a major factor for chatter. Normally, it is originated from the unbalance of the rotational components of machine tools or impact during performing intermittent cutting using multi-tooth tools.
4. Self-excited vibration – initiated from negative damping phenomenon of cutting system as energy keeps surging in due to increased processing load. It is also called chatter in the application of machine tools.

Toh [1] elucidated and compared the employment of up milling and down milling using static and dynamic cutting force and analysis of variance analysis in order to gain an in-depth understanding on its effects on tool life results obtained via the parametric study of alternative cutter path strategies when high speed milling hardened steel. The study further evaluated the three-dynamometer cutting force components in order to identify which component is the most sensitive to tool wear and cutting conditions applied. Static and dynamic cutting force analysis suggested that the static normal force is the most sensitive to tool wear and cutting conditions imposed.

Chiou and Liang [2] presented an analytical model for acoustic emission dynamics in orthogonal cutting with chip thickness variation. An analytical expression for acoustic emission generated in turning was established as an explicit function of the cutting parameters and tool/work piece geometry. Based on the theoretical static cutting acoustic emission model, the generation of the RMS acoustic emission was formulated as the function of three process parameters, namely tool displacement, cutting speed, and rake angle. The incremental change of the RMS acoustic emission is related to the chip formation process in an elemental cutting area and it is characterized by the dynamic variation of these process parameters.

Li and Li [3] presented a predictive time domain chatter model for the simulation and analysis of chatter in milling processes. The model was developed using a predictive milling force model, which represents the action of milling cutter by the simultaneous operations of a number of single-point cutting tools and predicts the milling forces from the fundamental workpiece material properties, tool geometry and cutting conditions. The instantaneous undeformed chip thickness was modeled to include the dynamic modulations caused by the tool vibrations so that the dynamic regeneration effect is taken into account. A proposed method [4] was based on the interrupted cutting of a specially designed workpiece that provides a strong broadband excitation. A method was proposed to identify the nine terms of the dynamometer transfer matrix from only one cutting configuration under normal machining operation. The determined transfer matrix was used for dynamic cutting force compensation under some milling operations.

Chiou and Liang [5] presented an analysis of the chatter behavior for a slender cutting tool in turning in the presence of wear flat on the frank. The mechanism of a self-excited vibration development process with tool wear effect was studied. The components contributing to the forcing function in the turning vibration dynamics were analyzed in the context of cutting force and contact force. Stability plots were presented to relate width of cut to cutting velocity in the determination of chatter stability. The use of an active dynamic absorber to suppress machine tool chatter in a boring bar was studied [6].The vibrations of the system are reduced by moving an absorber mass using an active device such as an piezoelectric actuator, to generate an inertia force that counteracts the disturbance acting on the main system. A cutting process model that considers the dynamic variation of shear and friction angles, that causes self-excited chatter during the cutting process, was applied to the lumped mass model. The theory of regenerative chatter was also applied to the model. Stability boundaries have been calculated for maximum permissible width of cut as a function of cutting speed.

Shi et al. [7] developed a unified nonlinear time series analysis approach to the problem of feature extraction of machine tool chatter. Considering the mechanism of chatter development, the procedure proposes the limit cycle behavior of self-excited random vibration to be the intrinsic index of chatter occurrence, and provides the exponential autoregressive model to extract the index from on-line measured machining signal.

Kondo et al. [8] introduced a new criterion for detecting regenerative chatter by application of spectral analysis. It can be seen that the vibration amplitude perpendicular to a workpiece surface comes equal to the amplitude of surface undulation at the stability limit. Validity of this criterion was examined by using numerical simulations assumed to be orthogonal, and then experiments for verification of criterion validity were carried out using the regenerative chatter of a turning workpiece in orthogonal cutting.

Altintas and Budak [9] presented a new method for the analytical prediction of stability lobes in milling. The stability model requires transfer function of the structure at the cutter-workpiece contact zone, static cutting force coefficients, radial immersion and the number of teeth on the cutter. Analytically predicted stability lobes were compared with the lobes generated by time domain and other numerical methods available in the literature.

Smith and Tlusty [10] described the theoretical basis behind a system for the elimination of chatter in milling through the automatic regulation of the spindle speed. This technique is most effective in milling operations where the tooth passing frequency can approach the natural frequency of the mode responsible Experimental data were quoted to illustrate typical improvements in metal removal rate.

Schmitz [11] applied receptance coupling substructure analysis to the prediction of the tool point dynamic response, combining frequency response measurements of individual components through appropriate connections to determine assembly dynamics using simple vector manipulations.

Altintas and Engin [12] presented a generalized modeling of arbitrary end mills or inserted cutter geometry. The cutting edge along the helical flute or along the arbitrary inserts were modeled mathematically. The chip load at each point along the cutting edge is identified by combining the rigid body kinematics of milling and structural dynamic deformations of cutter body and workpiece. The proposed approach allows the design and analysis of a variety of milling operations used in industry.

Su et al. [13] introduced a new approach for predicting chatter in high-speed end milling by using a fuzzy neural network. A milling experimental setup was built and a set of the valuable experimental data was acquired under different tool wear states and carefully selected cutting parameters. Then, the experimental system was simplified into a fuzzy neural network model which is trained in the experimental date. Some simulation results were thus obtained on the basis of the trained model. Finally, the calculated results were compared with the experimental ones in order to check the effectiveness of the method described.

Dynamic cutting processes and dynamic characteristics of the structure of machine tool determine cutting stability during cutting. The interrelation between the influential factors and five-axis cutting stability is shown in Fig.1, where the line with arrows at both ends indicates that the corresponding factor has interaction with the latter. These include structure deformation, dynamic cutting force, and tool wear. The figure also shows that geometric characteristics of curve, material of workpiece, cutting condition, and five-axis cutting strategy are all the influential factors as well. The factors mentioned above all possess deterministic influence on generating chatter and noise during cutting and thereby degrading surface roughness of the workpiece or producing various undesirable forms of chip. They can be compared and sorted out the most significant factor for further analyzing and investigation.

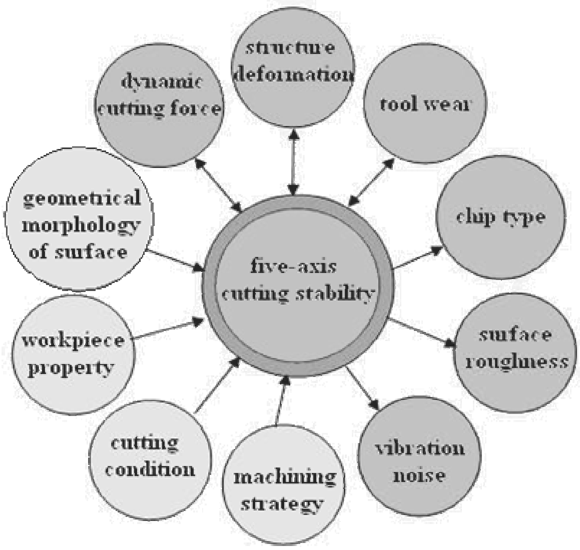


Fig. 1. Interaction between five-axis cutting stability and the corresponding influential stability

2. Related theory

2.1. Types of chatter

Basically, self-excited chatter can be classified as three types:

1. Regenerative chatter: It is due to wave on wave during successive cutting. As indicated in Fig. 2, if some hard spots existing in a workpiece or random fluctuation occurring during cutting result in relative motion between the tool and workpiece, wave-like ripples remain on the surface of the workpiece after cutting and subsequently change the amount of thickness to be cut. This will then generate dynamic cutting force which drives the tool and workpiece to vibrate and again undesirably affect thickness of undeform chip.

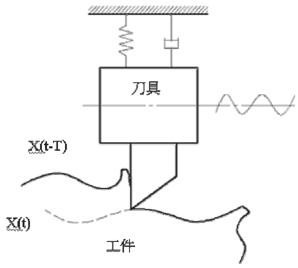


Fig. 2. Chatter with Regenerative Effect

2. Mode coupling chatter: Since practical cutting system possesses more than one degree of freedom (DOF), there exists coupling phenomenon on motion characteristics in each direction. This type of chatter is found in a cutting system with more than two degrees of freedom. A simple example is shown in Fig. 3. This system composes of two springs with different stiffness connected to a mass. The direction X_1 and X_2 are mutually normal, and the stiffness in direction X_1 is greater than that in direction X_2 ($K_2>K_1$).

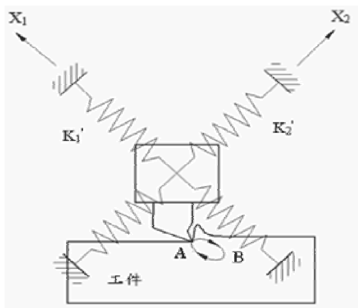


Fig. 3. Chatter with Coupling Mode of 2 DOF

3. Chatter due to falling characteristic of cutting force: In cutting processes for most workpiceses, cutting force will get higher as cutting speed gets lower. As shown in Fig. 4, when the tool moves toward right direction during vibration, the effective cutting speed relative to the workpiece decreases by an amount of $\dot{Z}$, and vice versa. Therefore, the vibration toward right and left direction results in decrease and increase of

cutting force, respectively. This characteristic that variation of the cutting force is dominated by vibration is a major cause for dynamic instability.

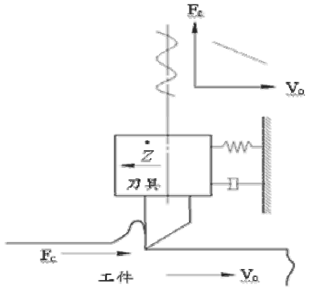


Fig. 4. Chatter due to Falling Characteristic of Cutting Force

2.2. Fourier series transform

Basically, there are four different forms for Fourier series transform and are presented by formula and graphical illustrations as follows:

a. Integral Transform

$$G(f) = \int_{-\infty}^{\infty} g(t) e^{-j2\pi ft} d(t) \tag{1}$$

$$g(t) = \int_{\infty}^{-\infty} G(f) e^{j2\pi ft} df \tag{2}$$

Both of them being continuous in frequency and time domains

b. Fourier Series

$$G(f_k) = \frac{1}{T}\int_{0}^{T} g(t) e^{-j2\pi f_k t} dt \tag{3}$$

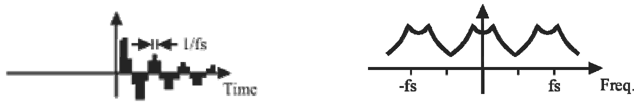
$$g(t) = \sum_{k=-\infty}^{\infty} G(f_k) e^{j2\pi f_k t} \tag{4}$$

Being discrete in frequency domain and periodic in time domain

c. Sampled Function

$$G(f) = \sum_{n=-\infty}^{\infty} g(t_n) e^{-j2\pi ft_n} \tag{5}$$

$$g(t_n) = \frac{1}{f_s}\int_{0}^{f_s} G(f) e^{j2\pi ft_n} df \tag{6}$$



Being periodic in frequency domain and discrete in time domain

d. Discrete Fourier Transform

$$G(f_k) = \frac{1}{N}\sum_{n=0}^{N-1} g(t_n) e^{-j\frac{2\pi nk}{N}} \tag{7}$$

$$g(t_n) = \sum_{k=0}^{N-1} G(f_k) e^{j\frac{2\pi nk}{N}} \tag{8}$$

Both of them being discrete and periodic in both frequency and time domain

3. Experiment set-up and execution

The accelerometer with piezoelectric charge type was utilized in this experiment and it is connected to an accelerometer coupler to amplify the acquired signal. Next, the sampled signal was processed via spectrum analyzer displaying some relevant function transformation to investigate the properties and characteristics of the dynamic cutting behavior during a free surface cutting. PowerMILL CAM software was utilized for five-axis machining of a free surface, which has a simultaneous 3~5 axes movement control function in its commercial modulus. Different machining strategies based on a complicated geometrical theory may be flexibly selected and combined together on its user interface via graphical icon, user may learn and be familiar with its operation easily during a short period. The main function difference between three-axis and five-axis in it is only the setting of cutting tool orientation and projection direction. PowerMILL with multi-axis function may fully be applied on fixed direction machining, multi-axis mill and simultaneous five-axis continuous movement machining. The collision between workpiece and jig during the spindle head moving or change tool orientation may also be avoided definitely.

The geometrical profile of a free surface machining in experiment is shown in Fig. 5. This multiple free surface may be machined successfully through a simultaneous five-axis movement machining strategy having a 5 degree-of-freedom path motion driven by the servomotor. It is based on a projection machining manner and this machining strategy for a prescribed amount of the tool-workpiece contact angle and the overhang length of the cutting tool maintenance may be ensured during a multiple free surface machining process. The cutting tool path is automatically generated as shown in Fig. 5 for a free surface machining based on this machining strategy, the moving orientation of the cutting tool pass and the square boundary of the free surface may keep a 45^{o} inclination angle.

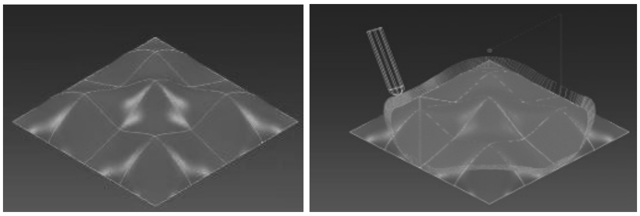


Fig.5.Geometrical profile of a free surface and its cutting tool path planning

Figs. 6 and 7 show a schematic diagram for the measurement apparatus set-up, the accelerometer was adhered to the location where is most sensitive to cutting vibration during machining process. CNC-rotary-table is the weaker zone of this machine tool and that has detected from the results of the modal analysis performed previously. The cylindrical bar workpiece is mounted on the chuck along the c-axis, the cutting force interacted between workpiece and tool has a large part concentrated around this area. Hence, the accelerometer was adhered at the back surface of the b-axis rotary element of the CNC-rotary-table, where is the most sensitive site to sensor the possible indirect vibration induced during a free surface machining. Since the accelerometer is not able to adhere to cutting tool and work piece to detect the cutting vibration signal directly. This acquisition manner is adopted to detect the indirect vibration signal suitably. In this study, accelerometer is adhered to the location where is the intersection point between the bottom surface swing about the b-axis and the extension line of the c rotational axis as described in Fig. 7 in detail. This adhesion action accounted for the cutting behavior of the CNC-rotary-table with acting force transmission natures. The selection of adhered site is not only for the vibration state of the swing action during the free surface machining but also for that signal direct detection.

Pure aluminum cylindrical bar and high-speed steel were used as workpiece and end mill, respectively in experiment. The diameter of end mill is 6 mm with three cutting edges. The depth of cut and rotational speed were selected as machining parameters, combinations of depth of cut and rotational speed of the cutter as the cutting parameter factors. Refer to workpiece properties, each three levels of cutting parameter were set as 0.1, 0.2, 0.3 mm for depth of cut and set as 4000, 5500, 7000 rpm for cutter rotational speed. Cutting path is automatically generated through CAM software based on the geometrical profile of the machined surface. Through the combinations of machining parameters, 9 cutting condition sets can be constituted. To detect the acceleration along the three mutually perpendicular axes, xyz, at the most sensitive location and result data of 27 sets through the simultaneous five-axis movement cutting experiment is thus obtained. Fig. 8 shows the flow chart pertaining to execution procedures for a five-axis cutting stability experiment. After undertook the analysis and comparison of the data sampled from the experiment, the influence of the variations of cutting parameter on the cutting stability performance can thus be ascertained.

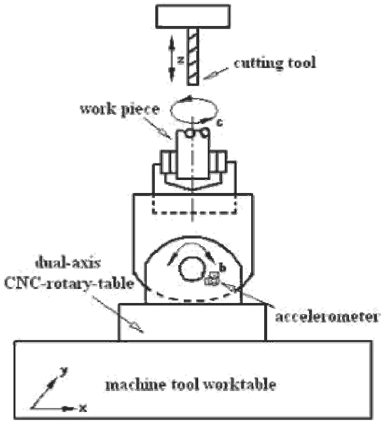


Fig. 6. Schematic illustration of a dual-axis CNC-rotary-table configuration and the indication on that table for accelerometer adhesion in experiment

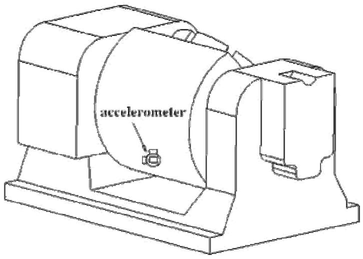


Fig. 7. Schematic diagram for the adhesion location of an accelerometer for vibration detection (detailed indication)

4. Result and discussion

The vibrational behavior of the CNC-rotary-table with various combinations of process parameters can be investigated in both frequency and time domain through the spectrum analyses of the measured data. This can be indirectly utlilized to determine the relative cutting stabilities among these experimental cases. The spectrum analysis indicates that, as operated under no cutting action at a rotational speed of 4000, 5500, and 7000 rpm, considerable spikes of response amplitude can be detected at the three-direction frequency of 60 Hz and 536 Hz, where the former is the natural frequency of the table and the latter is that of the

CNC-rotary-table. Based on these data, the researchers can further examine whether various combinations of the process parameters can stimulate larger response respect to the frequency of 536 Hz of the CNC-rotary-table or the other frequencies.

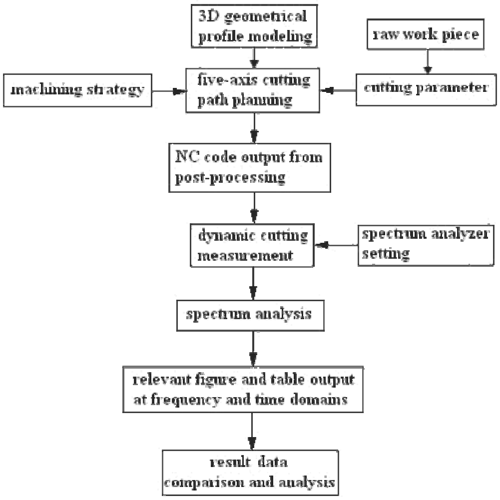


Fig. 8. Flow chart for a five-axis cutting stability experiment

The experimental data obtained from the cases with and without a real cutting process find that a test under a specified rotational speed can generate its own characteristic 3-direction frequencies. The paper specially select the characteristic frequency with the most significant change on response amplitude to analyze. The chosen frequencies corresponding to the rotational speed of 4000, 5500, and 7000 rpm are 132, 184, and 116 Hz, respectively. The results shown on frequency domain for identifying characteristic frequencies can be interpreted on time domain to observe amplitude variation respect to time and further understand its changing pattern under the cutting process.

4.1. Spectrum analysis for the effect of depth of cut on cutting stability

The content shown in Fig. 9 is a typical vibration spectrum along x direction in frequency domain under the cutting depth of 0.1 mm, 0.2 mm, and 0.3 mm at the rotational speed of 4000 rpm. The other vibration spectrums along y and z directions at the other rotational speeds of 5500 and 7000 rpm all have the same distribution pattern as shown in this figure. The trend of amplitude distribution agrees with the common vibration modes of a machine tool. It is clear that all the characteristic frequencies lie within lower frequency region (below 600 Hz). The vibrational energy in this region is relative higher than that in higher frequency region. Comparison among in each figure (a), (b), and (c) conditions under a specific rotational speed implies that a larger depth of cut causes a larger energy level of vibration. This is because depth of cut is one of the major factor in cutting processes. Increasing depth of cut can enlarge the contact area between tool and surface of workpiece. The tool must withstand a larger cutting force to effectively remove chip. However, during the cutting process with five axes moving simultaneously and the position of each axis changing constantly, the corresponding dynamic cutting force may reveal an unstable phenomenon. A larger cutting force can easily result in a more unstable state, and thus induce a larger vibration amplitude. In the region of high-frequency spectrum, the signal pattern of vibration due to various depths of cut changes with different rotational speeds. It can be explained that fracture on the cutting surface causes some chips rubbing each other in the cutting region. In the case of 4000 rpm rotational speed, relative low friction generated by low vibration energy is not sufficient to excite response of the corresponding characteristic frequency. As for 5500 rpm, increased forces accompanied by increased depth of cut enhance the amplitude response in high-frequency region so that amplitude spikes can be observed in the case of depth of cut of 0.2 mm at 1.9 kHz and 2.3 kHz. Finally, in the case of 7000 rpm, the highest one compared with the other two, the correponding amplitude reponse is the most significant. However, variation on depth of cut does not notably change the values of characteristic frequency.

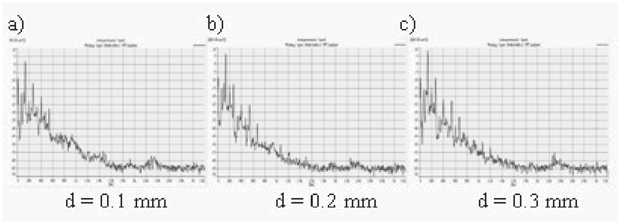


Fig. 9. Frequency spectrum along x-direction for different depths of cut at 4000rpm rotational speed

4.2. Exhibition of time-domain signal at specific frequency during cutting process

This section focuses on the continuous time-varying pattern of the frequency signal with maximum response at each rotational speed. Fig. 10 reveals the relationship between vibration amplitude of acceleration and elapse time corresponding to various depth of cut at a specific rotational speed.

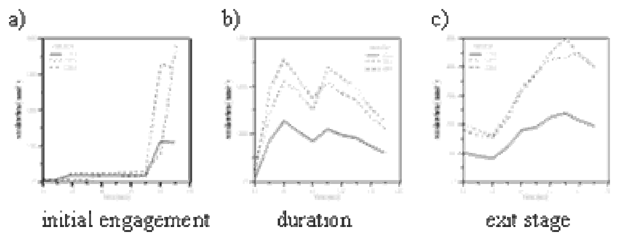


Fig. 10. Relationship between vibration amplitude of acceleration and elapse time corresponding to The dynamic-behavior measured at time domain along x-direction under the rotational speed of 4000 rpm at three consecutive cutting stages

4.3. Analysis of relation between depth of cut and cutting stability along different directions

Figs 11, 12, and 13 show the trends of vibration amplitude of acceleration and elapse time along each x, y, z direction for different depths of cut at the rotational speed of 4000, 5500, and 7000 rpm, respectively. Each figure contains nine subplots arranged in three columns which correspond to the three cutting stages of engagement, duration, and exit, respectively. It can be observed that the vibration levels for the case with depth of cut of 0.1 mm are the smallest among all, a larger depth of cut indicates a larger vibration level due to increased cutting force. However, even though the difference of amplitude between the conditions of depth of cut of 0.2 mm and 0.3 mm is not so obvious, we can still find that the amplitude with the cases of 0.2 mm is generally smaller than those of 0.3 mm.

Now, we continue to compare the results among the three cutting stages. In the stage of engagement, since the tool has not contacted with the workpiece yet, the vibration level along z direction is considerably large compared with that along x and y directions. As the tool initially engages the workpiece, the CNC-rotary-table mounted on the table starts to move, and then enhances the vibration amplitude along x and y directions. It should be also noted that the y direction coincides with that of center line of b axis. Hence, swinging the rotary-table back and forth about b axis does not stimulate vibration response along y direction. Then, it can be detected that the vibration level along x direction is comparably larger than that of y direction.

When the cutting process is gradually stabilized, the varying trends of amplitude are all similar, as shown in the subplot (x2), (y2), and (z2) of Figs 11, 12, and 13. Moreover, the swinging movement about b axis generates a constantly-swinging coordinate of x and z on the diving plate relative to a stationary coordinate of x and z on the table. This results in correlation between the vibration amplitude along x direction and z directions. That is to say, a larger vibration amplitude along x direction is accompanied with a smaller one along z direction and vice versa.

Additionally, the vibration amplitude along y direction also increases due to a rotational effect along c axis. As the process enters the final stage of exit, the accelerometers along all five axes start to return to their original reference points, and the resulting displacements make the measured vibration levels along each direction naturally increased, as revealed in the corresponding subplots (x3), (y3), and (z3) of Figs 11, 12, and 13.

The magnitude of vibration amplitude depends on the position swung about b axis and phase angle rotated relative to c axis during the transient state before entering the stage of exit.

Hence, a larger displacement relative to these two axes for returning their original points induces a larger measured vibration amplitude.

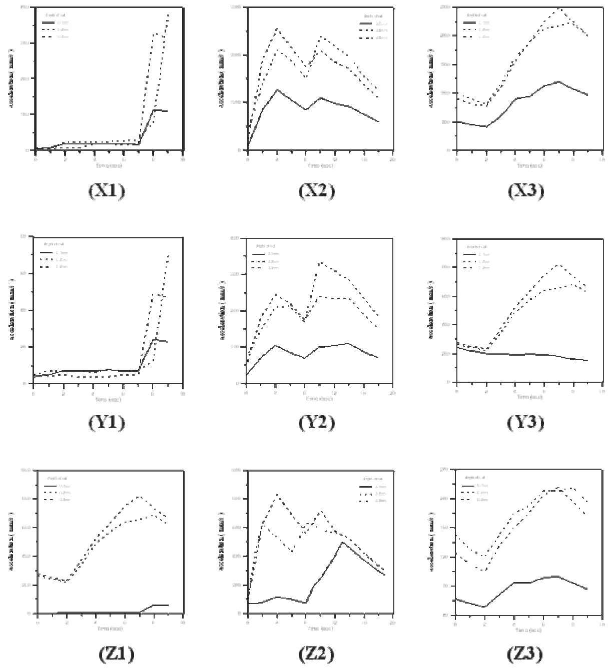


Fig. 11. Relationship between vibration amplitude of acceleration and elapse time along each x, y, z directions for different depths of cut and 4000rpm rotational speed at three consecutive cutting stages. (Note: left to right graphs represent cutting at different stages: initial engagement, duration and exit moment)

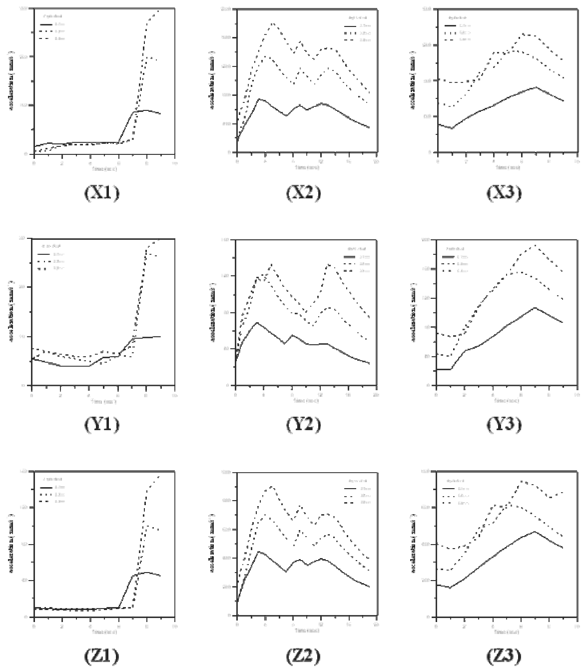


Fig. 12. Relationship between vibration amplitude of acceleration and elapse time along each x, y, z directions for different depths of cut and 5500 rpm rotational speed at three consecutive cutting stages

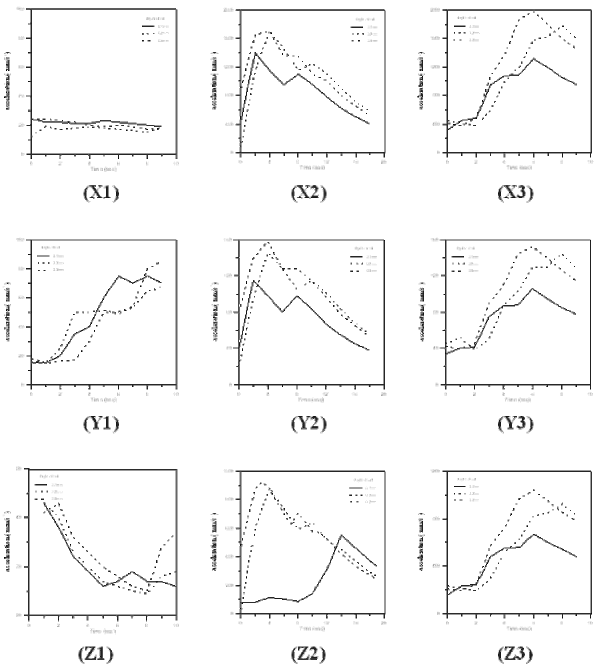


Fig. 13. Relationship between vibration amplitude of acceleration and elapse time along each x, y, z directions for different depths of cut and 7000rpm rotational speed at three consecutive cutting stages

5. Conclusions

In order to analyze the cutting stability in the five-axis free surface machining, a multi-dimensional free geometric curve is specially designed and a CAM software for path planning of a tool is adopted to organize a processing program for simultaneous five-axis movement. Depth of cut associated with rotational speed of tool is selected as the factor of process parameters. Considering the characteristics of the selected material of the workpiece and machine tool, Based on a full-factor experimental design with three selected values of depth of cut and rotational speed as inputs, totally nine processing paths of simultaneous five-axis movement are deliberately planned. An accelerometer on bottom surface of b-axis of the dividing plate is utilized to monitor and acquire the vibration signal in the cutting processes of the engagement, duration, and exit stages. Through the spectrum analysis for each case, the maximum amplitude of frequency response along three axes can be obtained so as to investigate and compare the relative cutting stabilities. Thereby, the following conclusions can be drawn:

1. The vibration levels of the depth of cut of 0.1 mm are the smallest among all cases, no matter what direction is selected to measure. A larger depth of cut indicates a larger vibration level due to increased cutting force. However, even though the difference of amplitude between the conditions of depth of cut of 0.2 mm and 0.3 mm is not so distinguishable, we can still find that the amplitude with the cases of 0.2 mm is generally smaller than those of 0.3 mm. A larger depth of cut can generate a larger vibration level. However, varying the cutting force does not significantly change the characteristic frequencies.
2. Rotational speed of the spindle is the major factors for the response of the characteristic frequencies. Different patterns of vibration signal can be observed for different rotational speeds and depths of cut. Due to the friction effect in the cutting zone, the vibration response in the spectrum region of high frequency is moderate for lower rotational speed. As rotational speed increases, the global amplitude increases and the amplitude response in high-frequency region enhances.
3. The actions of both the displacing axis and swinging axis have considerable impacts on cutting stability. Both the swinging motion about b axis and rotation about c axis can affect the corresponding vibration amplitudes. A larger movement of these two axes is followed by a larger measured vibration amplitude.
4. Since a variable free-curve cutting path rather than a flat one is selected to process, the feed rate of cut can not keep as a constant and should be determined by considering the swinging angle of the tool and the calculated contact area between the tool and workpiece. Therefore, under a cutting condition for simultaneous movement of five-axis, the feed rate of cut keeps changing with time and thereby causes a variation of characteristic frequencies.

Acknowledgements

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