A simulated investigation on the machining instability and dynamic surface generation

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Abstract: In this paper, the authors propose the generic concept of machining instability based on the analysis of all kinds of machining instable behaviors and their features. The investigation covers all aspects of the machining process, including the machine tool structural response, cutting process variables, tooling geometry and workpiece material property in a full dynamic scenario. The paper presents a novel approach for coping with the sophisticated machining instability and enabling better understanding of its effect on the surface generation through a combination of the numerical method with the characteristic equations and using block diagrams/functions to represent implicit equations and nonlinear factors. It therefore avoids the lengthy algebraic manipulations in deriving the outcome and the solution scheme is thus simple, robust and intuitive. Several machining case studies and their simulation results demonstrate the proposed approach is feasible for shop floor CNC machining optimisation in particular. The results also indicate the proposed approach is

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useful to monitor the machining instability and surface topography and to be potentially applied in adaptive control of the instability in real time.

Keywords: machining instability, surface generation, surface topography, simulation

Nomenclature

b	width of cut (mm)
F_f	feed force (N)
F_r	normal force (N)
F_t	main cutting force (N)
$F_x^{(m)}$, $F_y^{(m)}$, $F_z^{(m)}$	Laplace transforms of the cutting forces in the X, Y and Z directions respectively
$G_{ab}(w)$	the relative response of the structure in *a*th direction due to a force acting in the *b*th direction when the other two force components are zero
G	transfer matrix
h	uncut chip thickness (mm)
$\boldsymbol{H}$	Height vector of the intersection points of the sequence tool path
i	the oblique angle (deg.)
$\boldsymbol{r}$	the projection of the intersection points of the sequence tool path on the XZ plane
R	tool nose radius (mm)
t_i	index for the tool tip position in the tangential direction

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t_j	index for the tool tip position along the feed direction
α_n	normal rake angle of cutting tool (deg)
β_n	normal friction angle (deg)
Φ_n	normal shear angle (deg)
η	chip flow angle (deg.)
τ_s	shearing yield stress (MPa)

1 INTRODUCTION

Chatter vibration as a primarily involved machining instability has been studied for several decades. The basic mechanism of chatter is the "regeneration of waviness", i.e. the vibrating tool leaves a wavy surface, which in turn excites the tool at the same frequency during the next tooth passage. Since the cutting force is proportional to the chip thickness, the structural modes in the overall machining system are self-excited and lead to unstable vibrations [**1**]. Since 1960s, many researchers including Tobias and Tlusty had developed the basic theory of machining chatter [**2-3**]. Based on their work, many useful guidelines were formulated for both machine tools designers and manufacturing engineers.

Hanna and Tobias carried out a study of face-milling and turning processes in 1970s [**1**], in which both structural nonlinearities and cutting force nolinearities were taken into account. Quadratic and cubic nonlineraities were included in a differential equation with constant coefficients and the stability of the zero solution was studied. A two-term harmonic balance scheme was used to determine the amplitude of the periodic motion following the instability. Tlusty and Ismail investigated the basic nonlinearity in machining chatter. Both turning and milling are considered. The mode coupling self-excitation was demonstrated [**3**]. Altintas et al have undertaken a lot of research on milling processes with stability analysis [**4, 5**]. They looked at the processes with many kinds of cutters and dropped the feed term from the expression for the instantaneous chip thickness prior to the stability analysis. To determine the onset of instability, they examined the stability of the zero solution of a linear homogeneous differential equation with constant coefficients. This equation was obtained after time averaging the periodic terms associated with the cutting force. They obtained an analytical expression for roots of the characteristic equation in terms of the system transfer function. This is useful for predicting the onset of instability, but not for investigating the post-instability motion. Davies et al have carried out the investigations on chatter in turning processes [**6**, **7**]. In the studies, they provided experimental, numerical and analytical evidence suggesting that the onset of segmented chip formation was the result of a hopf bifurcation in material flow. They introduced a concept of the local plastic deformation zone that accounted for indentation of the material near the tool tip. They also simulated and measured the chatter in diamond turning of aluminum [**8**]. A nonlinear chip area model was formulated as a function of the change in depth of cut between consecutive passes. The cutting model was deduced based on the chip area model and further extended to include an impact disturbance to the cutting process. The Simulations of the resulting tool displacement showed close agreement with experimental measurements.

So far, many aspects of self-excited machine tool vibrations or chatters have been discussed. In practice, however, many problems of poor work surface finish are due to forced vibrations and the methods of reducing forced vibrations should be known. Forced vibrations are usually caused by an out-of-balance force associated with a component integral with, or external to, the machine tool. Whereas a self-excited vibration is spontaneous and increases rapidly from a low vibratory amplitude to a large one, the forced vibration results in an oscillation of constant amplitude. The exploration on the chatter vibration enables the better understanding of machining instability in practice. However, there are many sources of nonlinearities in the machining process, which are difficult to be precisely defined by the regeneration theory alone.

In the work presented, the authors not only have researched the dynamic instability based on linear regeneration chatter theory but also attempted to cover all of the variables in the machining system. In this paper the turning process is taken as an example as it is the most typical machining process where a stationary tool normally removes chips from the circumference of a rotating workpiece. Milling processes are similar from the viewpoint of chatter analysis, where the cutting tool rotates and the workpiece remains stationary. Based on the corresponding cutting force, a novel modelling approach is proposed to model the dynamic turning and milling process. The approach is in the light of transfer functions and block diagrams which are used to represent the nonlinear factors or functions in particular. The approach and models developed can not only be used to predict the onset of instability, but also to illustrate the post-instability motion in time domain and to simulate the generation of the surface topography and the effects of various process variables on the surface generation.

2 CONCEPTION OF MACHINING INSTABILITY

From the machining point of view, with the designed machining conditions, a desired surface finish will be produced under the stable machining process. But as a complicated dynamic system, various mechanisms inherent in the machining process may lead the innately stable machining system to work at a dynamic instable status which invariably results in unsatisfactory workpiece surface quality [**9**]. The machining instability coined here is a new generalized concept, which includes all phenomena making the machining process departure from what it should be. For instance, a variety of disturbances affect the machining system such as such as self-excited vibration [**10**], thermomechanical oscillations in material flow [**11**], Feed drive hysteresis [**12**] etc., but the most important one is self-excited vibrations resulted from dynamic instability of the overall machine-tool/machining-process system [**5**]. However, sometimes the machining process is carried out with a relative vibration between the workpiece and the cutting tool especially in heavy cutting and rough machining in order to obtain high material removal rates. The relative vibration is not necessarily a sign of the machining instability for the designed machining conditions and prescribed surface finish. In another extreme case, ultra-precision machining or micro/nano metric machining, the relative vibration between the workpiece and the cutting tool is too small to be measured, but the machining is sensitive to environmental disturbances. The surface generated may be unsatisfactory because of the disturbance, even though the machining system itself operates in the stable state. Therefore, the machining instability is related to the level of the surface quality required and the designed machining conditions.

Depending on above conception, the authors summarize all kinds of machining instability and their features as listed in Table 1 [**13, 14**]. The instability is classified as the chatter vibration, which includes regenerative, frictional, mode-coupling and thermo-mechanical chatter, and the random or free vibration usually includes any shock or impulsive loading on the machine tool. A typical random vibration is the tool vibration when the tool strikes at a hard spot during the cutting process. The tool will bounce or vibrate relative to the workpiece, which is the beginning of the phenomenon of the self-excited vibration. The initial vibration instigated by the hard spot is heavily influenced by the dynamic characteristics of the machine tool structure which must be included in any rational chatter analysis. Being different from the work carried out by others, this paper is not only focused on the chatter vibration, but also on the random and free vibration. Using the approach presented, the nonlinearities in the machining process will be modeled and analysed and thus the random or free vibration be quantitatively determined.

Table 1 The classification of machining instability

Machining Instability							
	Chatter vibrations				**Random and free vibrations**		
	Regenerative (Dominate)	Frictional	Mode coupling	Thermo-mechanical	Tool dependent	Workpiece dependent	Environment dependent

Location	Between cutting edge and workpiece	Tool flank –workpie-ce; Chip-too rake face	In cutting and thrust force directions	Tool-chip plastic zone	Tool flank –work-piece; Chip-rake face	Cutting zone	Whole cutting process
Causes	Overlapping cut	Rubbing on the flank face and the rake face	Friction on the rake and clearance faces; Chip-thi-ckness variation, shear angle oscillati-, on etc.	Temperatur-e and strain-rate affects chip formation	Tool wear and breaka-ge; BUE, etc.	Material soften and harden; Hard grain and other kinds of flaws	Environmental disturbances
Features	Self–excited vibration; Left a wavy surface on workpiece	Self-exci-ted vibration; Vibration amplitude depends on the system damping	Mode coupling vibration; Simultan-eous vibration in two directions	Velocity-dependent vibration	Rando-m and chaotic; Depen-des on cutting conditi-ons	Random and chaotic; Depends on material property and its heat treatment	Random and chaotic; Depends on work environment
Suppressi-on method	Select proper depth of cut and spindle speed according to regenerative stability chart	Select proper clearance and rake angles	Change the tool path; Select proper cutting varialbles	Select proper cutting speed	Select high quality tool materi-als and proper cutting parame-ters	Select proper cutting tool and cutting parameters	If needed, isolate the machine tool
Modeling	Linear differential equation	Nonlinear differenti-al equation	A set of linear different-ial equations	A set of partial and ordinary differential equations	Nonlin-ear factors in cutting process	Non-linear factors in cutting process	Non-linear factors in cutting process

3 MODELLING

3.1 Cutting force model of oblique turning process

The basic cutting force model is as follows [**15**] for typical oblique turning process as shown in Fig. 1.

$$F_t = bh \bullet [\frac{\tau_s}{\sin\phi_n} \frac{\cos(\beta_n - \alpha_n) + \tan i \tan\eta \sin\beta_n}{\sqrt{\cos^2(\phi_n + \beta_n - \alpha_n) + \tan^2\eta \sin^2\beta_n}}] \quad (1)$$

$$F_f = bh \bullet [\frac{\tau_s}{\sin\phi_n \cos i} \frac{\sin(\beta_n - \alpha_n)}{\sqrt{\cos^2(\phi_n + \beta_n - \alpha_n) + \tan^2\eta \sin^2\beta_n}}] \quad (2)$$

$$F_r = bh \bullet [\frac{\tau_s}{\sin\phi_n} \frac{\cos(\beta_n - \alpha_n)\tan i - \tan\eta \sin\beta_n}{\sqrt{\cos^2(\phi_n + \beta_n - \alpha_n) + \tan^2\eta \sin^2\beta_n}}] \quad (3)$$

where F_t, F_f and F_r are the main cutting force, feed force and normal force respectively. h is the uncut chip thickness, η is the chip flow angle, and b is the width of cut. τ_s is the shearing yield stress, β_n is the normal friction angle, and Φ_n is the normal shear angle. α_n is the tool normal rake angle and i is the oblique angle.

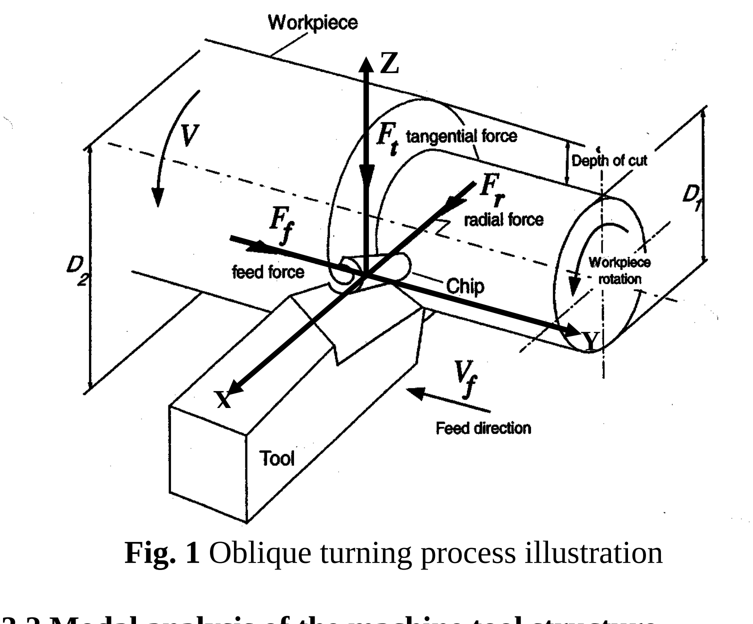


Fig. 1 Oblique turning process illustration

3.2 Modal analysis of the machine tool structure

Although the machine tool/cutting system is a very complex system, for its dynamics analysis it is sufficient to focus on the structural dynamics only at the cutting zone. The cutting force applied on the tool is decomposed into three components along there perpendicular directions as illustrated in Fig. 1. If $F_x^{(m)}$, $F_y^{(m)}$, $F_z^{(m)}$ are Laplace transforms of these forces, and $x^{(m)}$, $y^{(m)}$, $z^{(m)}$ are Laplace transforms of the relative displacement components between the tool and the workpiece, then the dynamics at the cutting zone can be expressed by the following matrix equation:

$$\begin{bmatrix} x^{(m)} \\ y^{(m)} \\ z^{(m)} \end{bmatrix} = \begin{bmatrix} G_{xx} & G_{xy} & G_{xz} \\ G_{yx} & G_{yy} & G_{yz} \\ G_{zx} & G_{zy} & G_{zz} \end{bmatrix} \begin{bmatrix} F_x^{(m)} \\ F_y^{(m)} \\ F_z^{(m)} \end{bmatrix} \tag{4}$$

where G is the transfer matrix. This matrix consists of nine transfer function elements. $G_{ab}(\omega)$ provides the relative response of the structure in *a*th direction due to a force acting in the *b*th direction when the other two force components are zero. For a linear system, the matrix **G** is symmetric ($G_{ab}=G_{ba}$). The assumption of linearity is generally accepted, although it is known that the static stiffness of the machine tool structure and guideways behave with non-linear characteristics. On the other hand, the nonlinearities can be expressed by special designed single block in the modelling and simulation. The nine transfer functions in Eq.(1) can be determined by structural dynamics test. The reference [**15**] provides quite useful information on the feasibility and experimental practices of determining the transfer functions.

3.3 Major aspects within the machining system

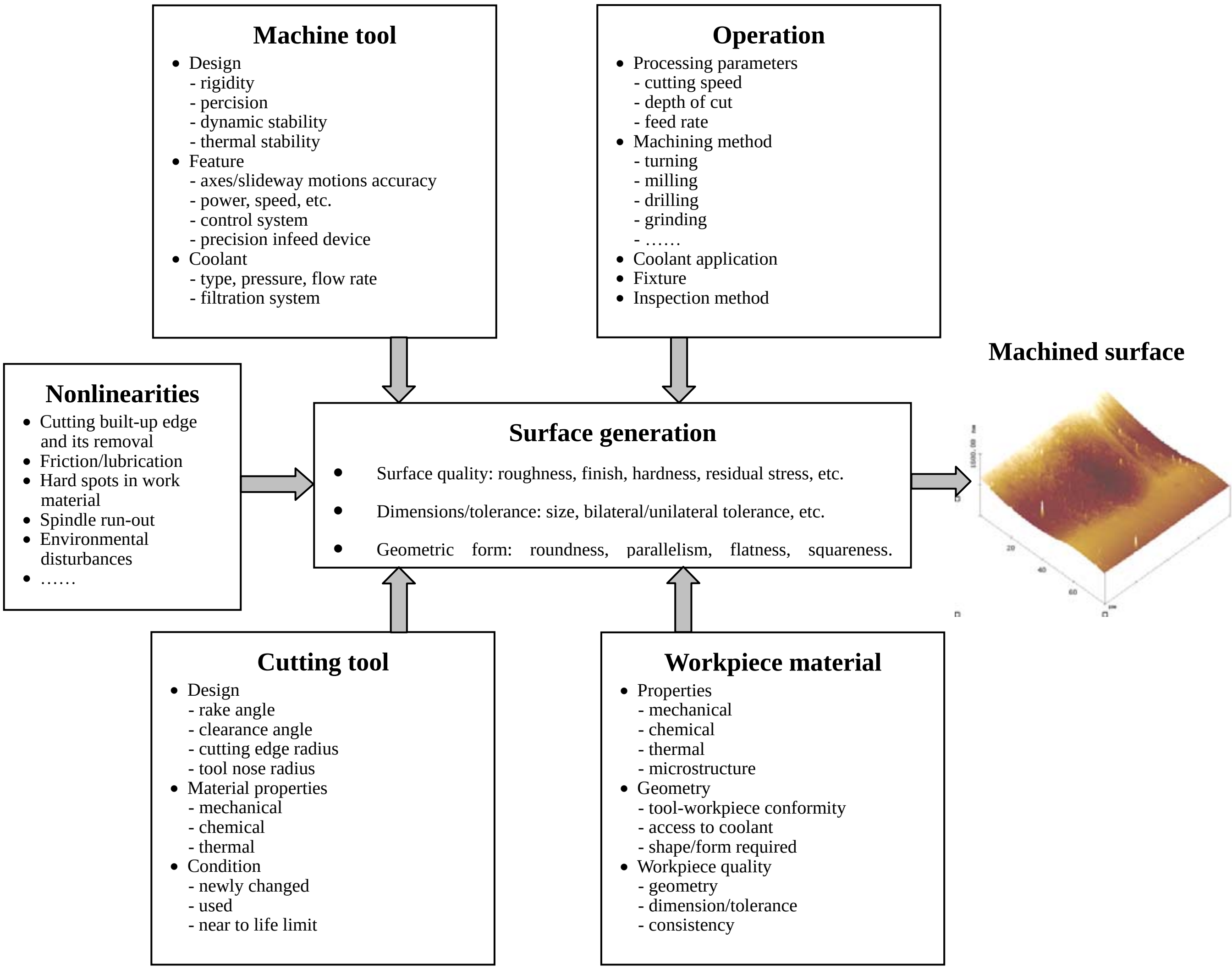


Fig. 2 Major aspects associated with the machining process

There are four categories of elements that particularly affect the machining process. They are the machine tool, operational factors, cutting tool, and workpiece material [**16**]. There are also many nonlinear factors in the machining process. These nonlinear factors were normally ignored in the past because of the difficulty and limitation of the modelling. Figure 2 illustrates the major aspects associated with the four categories of elements as well as the nonlinearity.

3.4 Modelling of the overall machining system

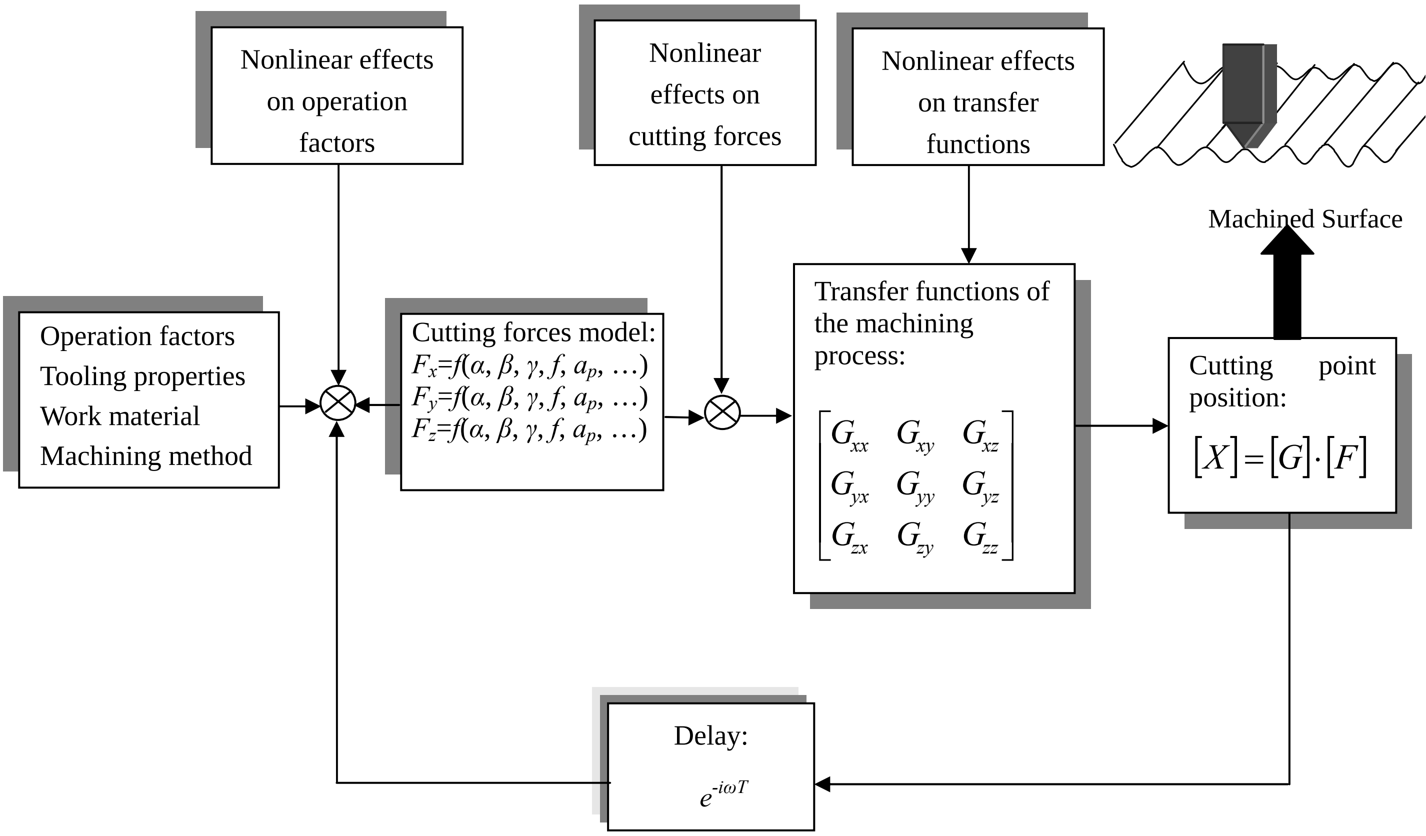


Fig. 3 A comprehensive model of the machining process

It is extremely difficult to model the whole machining system by using an exact mathematical model, since there are not only linear factors but also nonlinear factors in the process. Therefore, a block diagram model is proposed as shown in Fig. 3, to model the complicated machining process including the nonlinearity of the process. The model was implemented with MATLAB SIMULINK programming. The nonlinearity is built into the model by using different kinds of functions as specified. For instance, the sinusoidal function is used to denote the spindle imbalance which imposes an additional force acting on the machining system, the assumption is consistence with the error analysis on ultra-precision diamond turning machines by Precitech Inc. [**17**]. The amplitude of the sinusoidal function equals to the spindle specification provided by the Machine tool manufacturer, its frequency is just that of the spindle revolution; the intervally repeated ramp function denoted for the variation of the tool rake angle duo to the generation and removal of the built-up edge during the machining process, the frequency and amplitude of the ramp function can be acquired from the measured cutting forces; a series of impulse values randomly generated at regular intervals to emulate the workpiece hard spots and their effects on the work material’s characteristics, i.e. the changing of shear stress during the machining process. Furthermore, those non-linear factors can be switched on or off very easily and their effects on the surface generation can thus be interactively visualized and quantitatively investigated on the basis of an individual isolated event as specified. The proposed model can be used to predict the surface generated and to optimise the cutting conditions in the light of machining instability avoidance.

3.5 Modelling of the surface generation

Having set up the cutting conditions and the system transfer function and defined the nonlinear factors, the dynamic displacement between the cutting tool and the workpiece can be achieved by running the cutting system model. Taking the turning process as a case study, the modelling outcome will be the real tool path. After getting the real tool path on the workpiece, the intersection points of the sequence tool path are calculated by the following equation:

$$\begin{cases} r_{ti,tj} = \dfrac{2R(y_{ti,tj} - y_{ti+1,tj}) - (x_{ti+1,tj}{}^2 - x_{ti,tj}{}^2)}{2(x_{ti,tj} - x_{ti+1,tj})} \\ H_{ti,tj} = y_{ti+1,tj} + \dfrac{(r_{ti,tj} - x_{ti+1,tj})^2}{2R} \end{cases} \quad (5)$$

Where ***r*** and ***H*** are the projection on plane XZ and height vector of the intersection points of the sequence tool path, respectively. *ti* is the index for the tool tip position in the tangential force direction. *tj* is the index for the tool tip position along the feed direction. *R* is the tool nose radius. Trimming the line above the intersection points, the machined surface will be generated. Using the similar method, a milled surface can also be modelled and digitally generated.

4 SIMULATION AND EXPREIMENTAL VALIDATIONS

The whole machining dynamics model is implemented in a MATLAB simulink environment. It includes the cutting force module and machining system response module. In the turning process, the frequency of the ramp function for simulating the effects of BUE is about 5.25 Hz. It is assume that the increasing of the shear stress is ten percent of the initial shear stress due to the existence of hard spots in the workpiece materials. A delay function is used to represent the regenerative vibration effects on the variation of the depth of cut and the feed rate, its frequency is that of the spindle revolution.

Machining trials are carried out on a lathe to validate the model and simulation. The experimental configuration is shown in Fig. 4. The dynamic cutting forces are measured by a Kistler dynamometer, 9257BA, on which the carbide tool insert is mounted. The machined surfaces are measured by the Zygo Newview 5000 optical microscope. The aluminium alloy and steel sample components are turned in the experiments. The machining conditions are listed in Table 2.

Table 2 Machining trial conditions

Workpiece	Material	Al alloy/Low carbon steel
	Diameter	ϕ 50 mm

Cutting tool	Material	Carbide insert
	Nose radius	0.4, 0.8, 1.2 mm
	Initial side rake angle	0°, ± 5°
	Side clearance angle	0°, 5°, 7°
	Back rake angle	10°
	Back clearance angle	6°
Operation conditions	Spindle speed	490 rpm ~ 1400 rpm
	Feed rate	0.0397 mm/rev ~ 0.3175 mm/rev
	Depth of cut	0.01mm, 0.1 mm, 0.5 mm

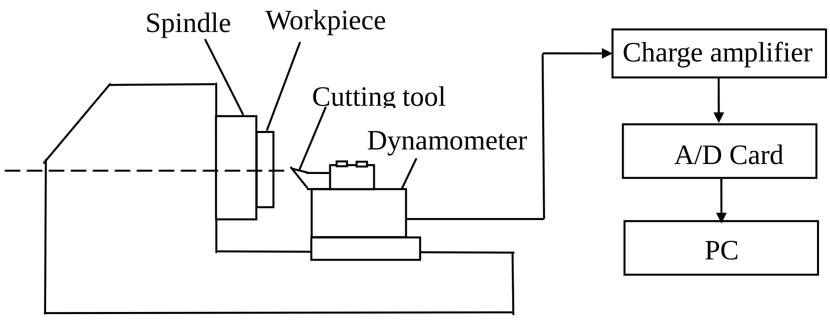


Fig. 4 Experimental configuration of the cutting trials

Figure 5 shows the simulated and measured cutting forces in the radial direction when the cutting is undertaken at the conditions: cutting speed = 1400 rpm, feed rate = 0.0397~0.3175 mm/rev and depth of cut = 0.01mm. It can be seen that the simulated cutting forces are well agreed with the measured results (about 38% lower than the measured results). The assumptions about the nonlinear factors are reasonable. It also shows the tendency that the radial cutting force increases with the increment of the feed rate. When the feed rate 0.0397mm/rev is applied, the simulated

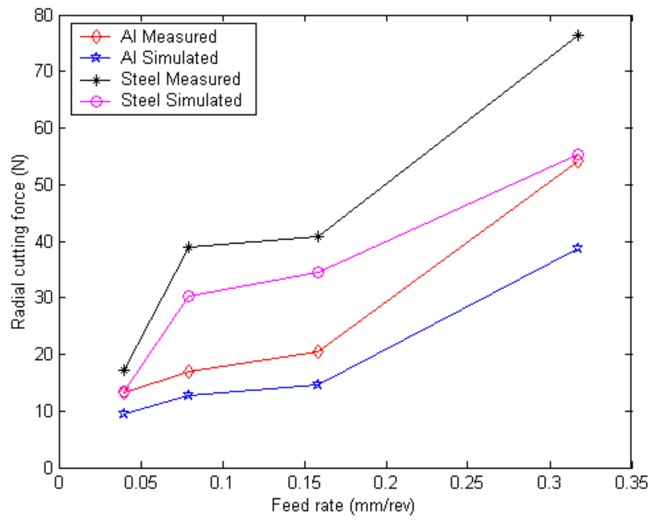
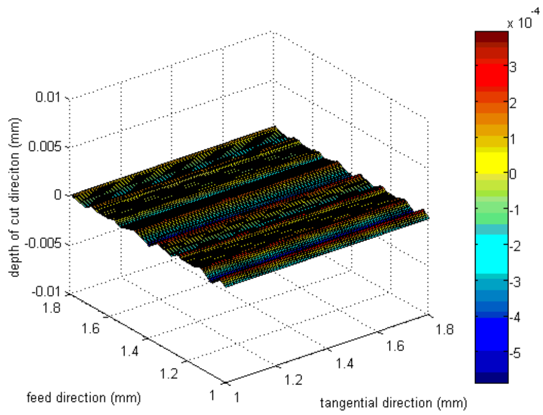
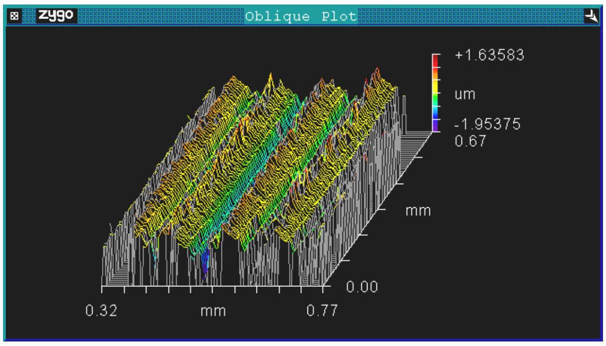


Fig. 5 The variation of the radial cutting forces with different feed rate



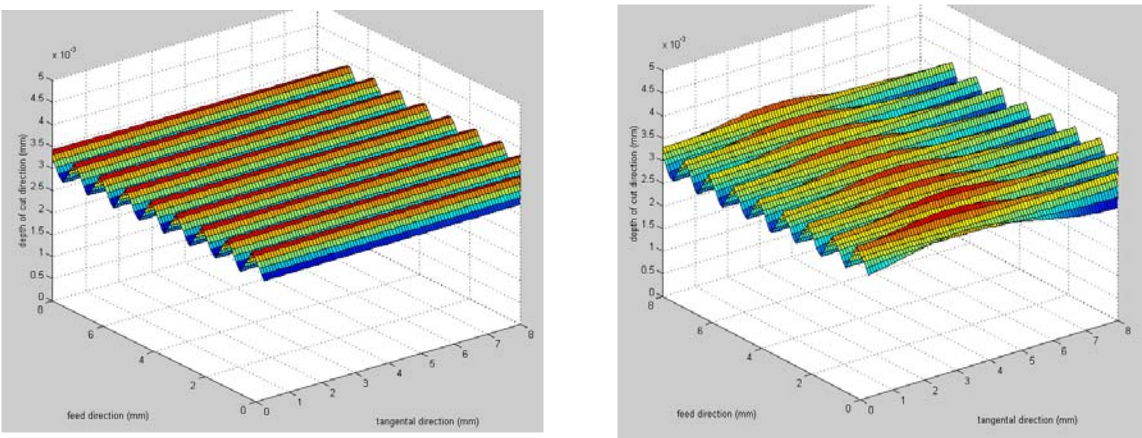


(a) Simulated surface

(b) Machined surfaces

Fig. 6 Comparison between the simulated surface and machined surface

machined surface and the measured surfaces are shown in Fig 6. The direction of lay is evident in both the simulated surface and the experimentally generated surface. The root-mean square deviation S_q of the simulated surface is 0.071 μm, which is close to the experimental result 0.14 μm. The difference between the simulation result and experimental result may be caused by the estimated static machining structural parameters. But the simulation results are still in the reasonable deviation scale.



(a) Turning without taking account of non-linear factors (b) Turning with taking account of non-linear

Fig. 7 Machined surfaces generated by the simulation

Two machining process cases are presented below. The turning process simulation is carried out with the spindle speed =1,400 rpm, depth of cut = 1.0 mm and Feed rate = 0.1 mm/rev. Figures 7(a) and 7(b) show two surfaces generated with and without taking account of nonlinear factors respectively. From the simulation results above, it can be easily found that these non-linear factors have much effect on the surface topography and texture produced.

5 CONCLUSIONS

In this paper, a novel modelling approach and the simulation system are presented with the case studies on turning and milling processes. The preliminary research findings include:

(1) The modelling and simulation approach proposed is based on combining numerical computing method, cutting mechanics, block diagrams and nonlinear functions to simulate the complexity of the machining system as a whole. It therefore avoids the lengthy algebraic manipulations in deriving the outcome and thus improves the simulation accuracy and comprehensiveness.

(2) A set of models is developed, which represents the dynamic characteristics of the machining system and also includes major non-linear factors within the machining process.

(3) The modelling and simulation developed can be used to predict the onset of the machining instability, but also to observe the post-instability motion in time domain.

(4) The approach contributes to the comprehensive understanding of the machining system. The models and simulation will assist the machining operators to select optimal machining parameters.

(5) The modelling and simulation will potentially lay down a foundation for researching on-line monitoring and control of the machining instability and its control algorithms.

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