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COMPUTER SIMULATION MODEL FOR SURFACE GENERATION IN TURNING PROCESS

نموذج محاكاة بالحاسب الآلي لتوليد الأسطح في عملية الخراطة

Ossama Abouelatta

Production Engineering and Mechanical Design Department, Faculty of Engineering, Mansoura University, 35516 Mansoura, Egypt

Email: abouelatta@mans.edu.eg

د. أسامة بديع أبوالعطا

قسم هندسة الإنتاج والتصميم الميكانيكي - كلية الهندسة – جامعة المنصورة

الخلاصة: من الممكن التنبؤ بتضاريس الأسطح المشغلة بدراسة التصرفات الاهتزازية لنظام التشغيل المكون من الماكينة والعدة القاطعة والمشغولة. وتهدف هذه الدراسة إلى إنشاء وتصميم برنامج محاكاة بالحاسب الآلي *(SurfGM)* للتنبؤ بخشونة الأسطح عند مختلف ظروف التشغيل، آخذاً في الاعتبار أهم العوامل المؤثرة في التصرفات الاهتزازية للماكينة والعدة القاطعة والمشغولة. وتتمثل هذه العوامل في متغيرات التشغيل ومتغيرات العدة القاطعة والمشغولة ومتغيرات الكتلة والجساءة والإخماد لنظام التشغيل المكون من الماكينة والعدة القاطعة والمشغولة. وقد استخدم برنامج Matlab Simulink™ ليفي بالتفاعل بين المستخدم والبرنامج بطريقة بسيطة وفعالة. ويتكون البرنامج من ثلاث وحدات وهي: وحدة الإدخال الرئيسية *(SurfGM)* ووحدة عرض المحاكاة *(SurfPreview)* ووحدة حساب عوامل خشونة الأسطح *(SurfRP)* بالإضافة إلى النموذج الديناميكي لمحاكاة النظام. وقد تم تصميم وبناء واجهات التطبيق للوحدات الثلاث باستخدام Graphical User Interface بهدف تسهيل التعامل مع البرنامج.

تم الأخذ في الاعتبار ظروف التشغيل المختلفة وخصائص العدة القاطعة على كيفية توليد الأسطح خلال عملية المحاكاة. قد تم تعزيز النتائج بعدة محاولات لعملية الخراطة بهدف تقدير وتأبيد نتائج برنامج المحاكاة المقدم. وقد أظهرت النتائج مساهمة البرنامج المقدم في تقديم مفهوم أفضل وأشمل لنظام التشغيل، وبالتالي يمكن استخدامه في التطبيقات الصناعية وكمصدر جيد لتحديد ظروف التشغيل المثلى بناءاً على متطلبات الأداء الوظيفي للمنتجات.

Abstract

The texture of machined surfaces can be predicted from knowledge of the vibratory behavior of the machine-tool-workpiece system. This study is initiated to develop a generalized computer based simulation for predicting surface roughness for any given conditions which takes into consideration the important parameters influencing the dynamic behavior of the machine-tool-workpiece system. The parameters considered in the simulation are: machining variables, tool and workpiece variables, and the mass, stiffness and damping of the machine-tool-workpiece system. Matlab Simulink^{TM} is used to interactively perform the simulation in a user-friendly, effective and efficient manner. The effects of machining variables and tooling characteristics on the surface generation are investigated through simulations. Turning trials have been carried out to evaluate and validate the presented approach and simulations. The proposed approach contributes to comprehensive and better understanding of the machining system, and is promising for industrial applications with particular reference to the optimization of the machining process based on the product/component surface functionality requirements.

Key words

Surface roughness – Vibration – Turning – Computer simulation

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Nomenclature

A_j	Instantaneous chip area
C_{xj}, C_{yj}	Tool nose center points at j^{th} tool mark
d_c	Depth of cut
f	Feed
$F(t)$	Dynamic cutting force
F_j	Dynamic cutting force at the j^{th} tool mark
i	Index for sampling intervals along the feed direction
j	Index for tool marks along the feed direction
k	Sampling number intervals along the feed direction
K_c	Specific cutting resistance
K_{cl}	Coolant correction factor
K_{tm}	Tool material correction factor
K_v	Cutting speed correction factor
K_{wr}	Tool wear correction factor
K_γ	Side rake angle correction factor
m	Total number of tool marks along the feed direction
M_s, K_s, C_s	Dynamic characteristics of spindle structure
M_t, K_t, C_t	Dynamic characteristics of tool structure
M_w, K_w, C_w	Dynamic characteristics of workpiece
n	Rotational cutting speed
t	Time
t_o	Time for one revolution of workpiece
$x_s(t), \dot{x}_s(t), \ddot{x}_s(t)$	Displacement, velocity and acceleration of spindle
$x_t(t), \dot{x}_t(t), \ddot{x}_t(t)$	Displacement, velocity and acceleration of tool
$x_w(t), \dot{x}_w(t), \ddot{x}_w(t)$	Displacement, velocity and acceleration of workpiece
v	Cutting speed
Z_{ct}	z-coordinate of the workpiece surface at the current path
Z_t	The resulting z-coordinate of the workpiece surface
Z_{pt}	z-coordinate of the workpiece surface at the previous path

1 Introduction

Surface finish is a factor of great importance in the evaluation of workshop production and considerable attention is now being focused on those measurements as a means of quality control. Such information can be used to assist in understanding critical machining attributes such as machinability, tool wear/fracture, machine tool chatter, machining accuracy and surface finish [1–4]. The capability of modeling cutting forces therefore provides an analytical basis for machining process planning, machine tool design, cutter geometry optimization, and online monitoring/control. Preliminary tests were carried out by Rakhit et al. [1], for turning operations with specific cutting conditions. It was shown that the produced surfaces of machined components consist of two superimposed profiles; theoretical profile due to operation kinematics; and random profile due to cutting edge vibrations.

Jang and Seireg [2-3], developed a generalized computer-based simulation for predicting surface roughness. Dimensional and surface roughness controls in turning were achieved by a newly developed measuring system based on an optical technique by Shiraishi and Sato [4]. This simulation was shown to give a good correlation with the extensive experimental study reported by Hasegawa and Seireg [5]. Zhang and Kapoor [6-7], presented a methodology leading to dynamic generation of surface topography under random excitation environment through computer simulation. The proposed methodology used the tool vibratory motion along with the tool geometrical motion to construct the topography of the machined surface.

A model for surface generation in a turning process was described by Moon and Sutherland [8]. This model was based on a wavelength decomposition methodology to characterize the wavelength structure of the experimental design. The model was studied analytically and examined via computer simulations. As a way of in-process evaluation of machined surfaces, a method to determine surface profiles and R_{max} during hard turning was proposed by Jang and Hsiao [9]. Then their cutting tests, using an inductance pickup and a computer for data analysis, were performed. Jang et al. [10], developed an on-line, real-time monitoring algorithm for controlling a machine in a flexible manufacturing system. The algorithm was developed to utilize the relative cutting vibrations between tool and workpiece. The cutting vibration signals of a specific frequency were superimposed onto the kinematic roughness, which was calculated by the tool edge radius and feed rate. A surface topography simulation model was established by Lin and Chang [11], to simulate the surface finish profile generated after a turning operation. The surface topography simulation model incorporated the effects of the relative motion between the cutting tool and the workpiece with the effects of tool geometry to simulate the resultant surface geometry.

A cutting model, which contains a vibration cutting process, was proposed by Xiao et al. [12]. Simulations of the chatter model exhibited the main features including chatter suppression and small-work displacement in vibration cutting. An analysis of the chatter behavior for slender cutting tool in turning, in the presence of wear flat on the tool flank, was presented by Chiou and Liang [13]. The components contributing to the forcing function in turning vibration dynamics are analyzed in the context of cutting force and contact force. The stability of outer diameter turning is explored by Marsh and Schaut [14], to extend previous results from the orthogonal turning geometry. A numerical approach was developed to determine the stability limit using a nonlinear chip area model. The results showed qualitative differences from the orthogonal cutting geometry. The role of machine parameters and tool geometry is explored using the verified model.

Another model for analytical evaluations of the cutting forces in orthogonal cutting was proposed by Hayajneh et al. [15]. The model utilized the known advantages of the model of a shear zone with parallel boundaries for steady-state orthogonal cutting. Thomas and Beauchamp [16] collected and analyzed cutting-force, tool-vibration and tool-modal-parameter data generated by lathe operating under dry turning of mild carbon steel samples at different speeds, feeds, depths of cut, tool nose radii, tool lengths and workpiece lengths. The analysis investigated the effect of each cutting parameter on tool stiffness and damping, and yielded an empirical model for predicting the behavior of the tool stiffness variation. Rao and Shin [17] presented a model of the dynamic cutting force process for the three-dimensional or oblique turning operation. The mechanistic force model was linked to a tool–workpiece vibration model to obtain dynamic force predictions. The dynamic force model developed was incorporated into a computer program to obtain time-saving chatter predictions.

A neural network model was developed by Karpat and Özel [18], which model the surface roughness and tool wear characteristics of hard turning. The results indicated that a system, where neural network is used to model and predict process outputs and particle swarm optimization, is used to obtain optimum process parameters. In addition, it can be successfully applied to multi-objective optimization of hard turning.

Therefore, the present work aims to build an easy-to-use graphical user interface program capable of predicting surface roughness by integrating a dynamic cutting force model, regenerative vibration model, machining system response model and tool profile model.

2 Surface Generation Methodology

Figure 1 represents the basic elements of surface generation methodology developed in the present work to study the mechanism of the dynamic generation of the machined surface profile. The methodology uses the tool vibration response and the spiral trajectory of tool geometrical motion to generate the surface profile.

2.1 Machine-Tool-Workpiece Modeling System

Figure 2 shows a three system components which are considered to have the major influence on the machining process which are: spindle structure, workpiece and tool dynamic characteristics, and the cutting forces [2].

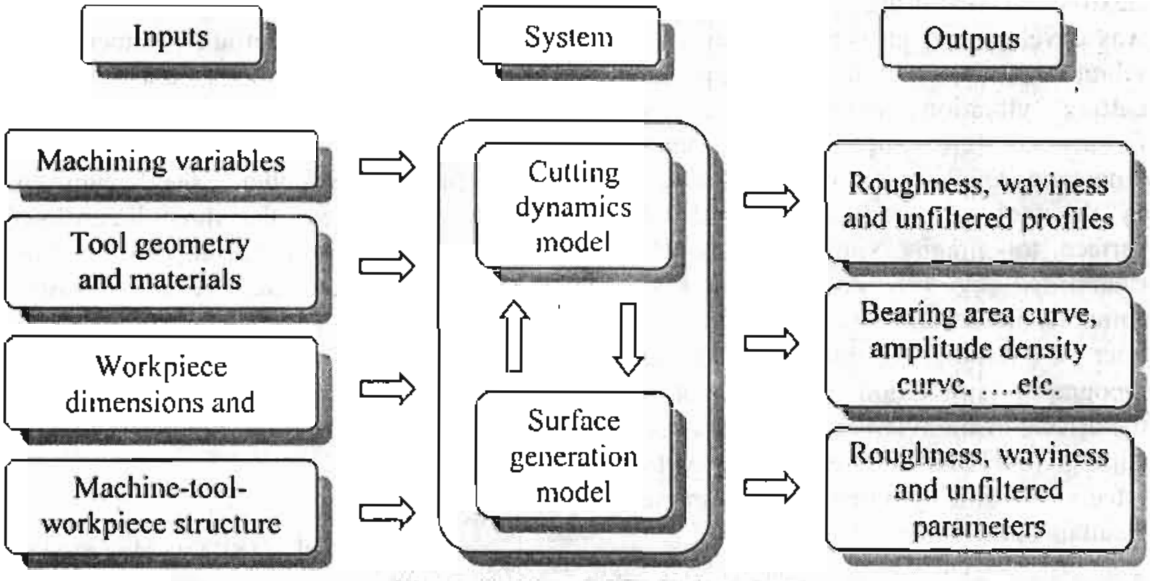


Fig. 1. Software block diagram.

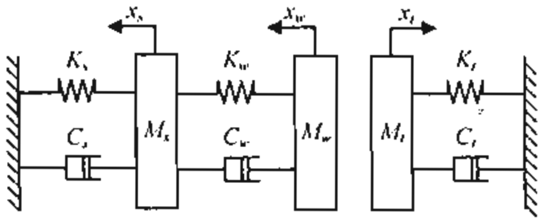


Fig. 2. Dynamic model of the system.

The proposed dynamic model of the system deals only with transverse movements while the axial movement is assumed to be negligible. The spindle structure is defied by M_s, C_s and K_s, the workpiece is defined by M_w, C_w and K_w and the tool is defined by M_t, C_t and K_t. The system response is defined by x_t, x_s and x_w.

The equations of motion for the system can be written as:

$$M_t\ddot{x}_t(t)+C_t\dot{x}_t(t)+K_tx_t(t)=F(t) \tag{1}$$

$$\begin{aligned}&M_w\ddot{x}_w(t)+C_w(\dot{x}_w(t)-\dot{x}_s(t))\\&+K_w(x_w(t)-x_s(t))=F(t)\end{aligned} \tag{2}$$

$$\begin{aligned}&M_s\ddot{x}_s(t)+C_s\dot{x}_s(t)+K_sx_s(t)\\&-C_w(\dot{x}_w(t)-\dot{x}_s(t))\\&-K_w(x_w(t)-x_s(t))=0\end{aligned} \tag{3}$$

2.2 Cutting Forces

The cutting force under steady state conditions can be reasonably considered to be directly proportional to the uncut chip cross-sectional area [19-24].

$$\begin{aligned}&F_j=K_c.K_\gamma.K_v.K_m.K_{wr}.K_{cl}.A_j\\&where\ \ (j=1,2,....,m)\end{aligned} \tag{4}$$

2.3 Tool Path Center Coordinate Equation

The center of tool nose radius coordinates can be evaluated as a function of feed, tool nose radius, cutting speed and depth of cut as:

$$C_{xj}=\begin{cases}0.1f & j=1\\ 0.1f+\dfrac{f.s.t}{60} & 1>j\geq m\end{cases} \tag{5}$$

$$C_{yj}=\begin{cases}d_c-r & j=1\\ C_{yj} & 1>j\geq m\end{cases} \tag{6}$$

2.4 Surface Profile Generation

Surface profile generation considers the tool geometry and effect of tool spiral motion. The surface profile can be calculated as the maximum height of the resulting tool marks as:

$$Z_i=\max(Z_{ai},Z_{pi}) \tag{7}$$

and the cross-sectional area, Fig. 3., for each turn can be calculated as the difference of current sum of areas and the previous sum of areas, as:

$$A_j=\sum_{i=1}^{n}Z_{i\,_{at\ j^{th}\ tool\ mark}}-\sum_{i=1}^{n}Z_{i\,_{at\ (j-1)^{th}\ tool\ mark}} \tag{8}$$

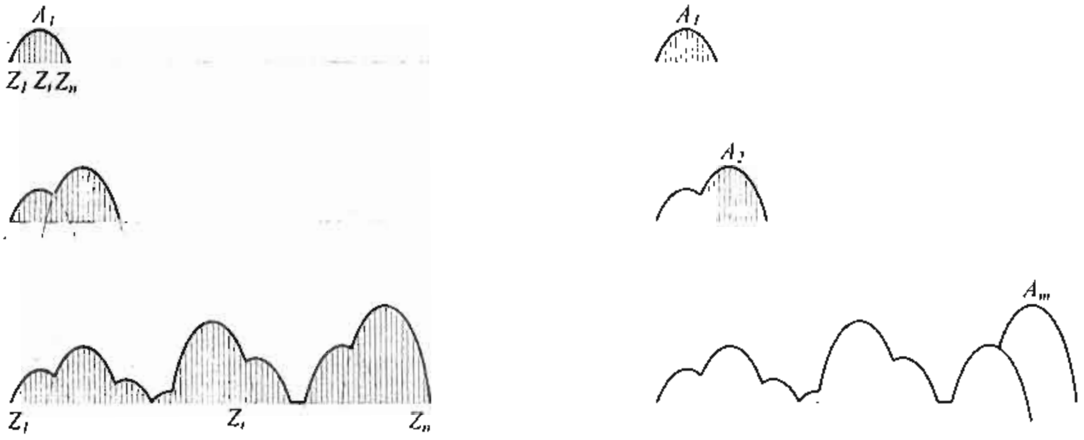


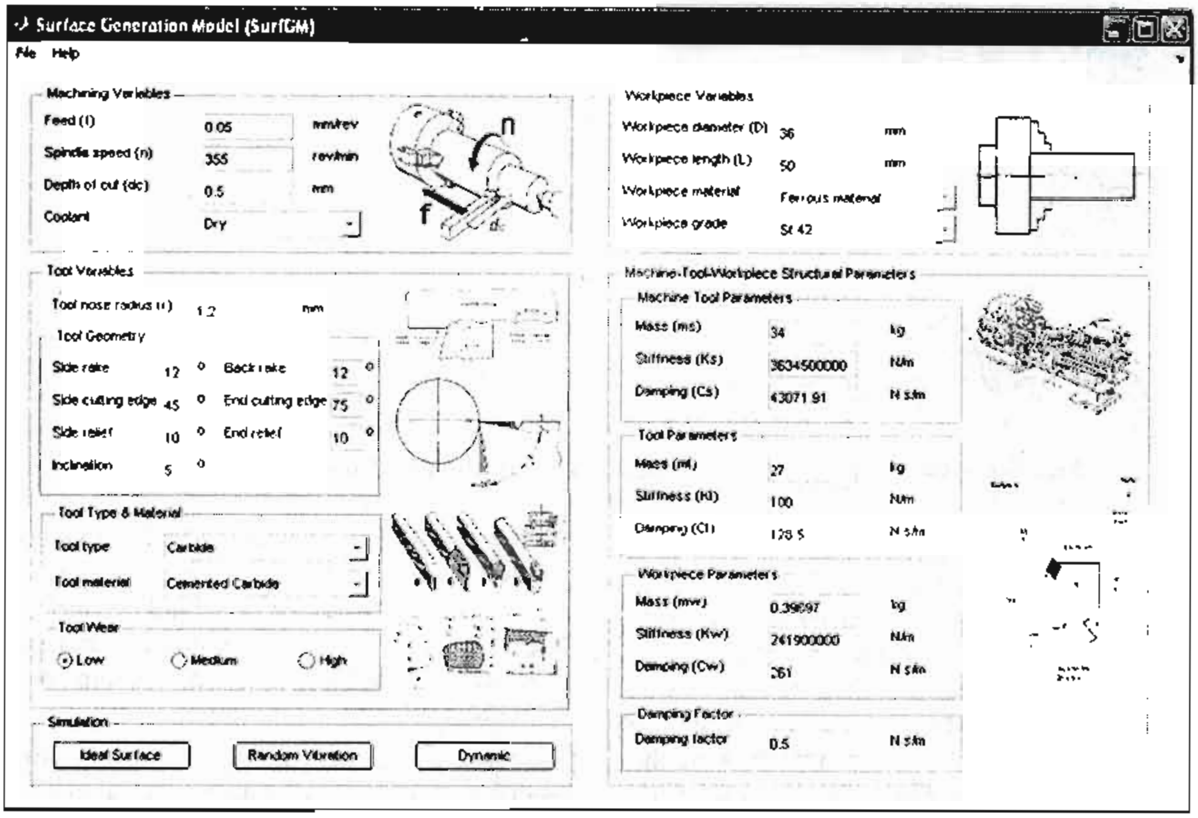
Fig. 3. Calculation of cross-sectional area and the resulting surface profile.

3 Simulation Software

Simulation software named Surface Generation Model, *SurfGM*, was purposely built for the implementation of the surface profile simulation model. The software was developed using MATLAB^{TM} programming language [25-27]. The main interface of the *SurfGM* is shown in Fig. 4. The inputs of the software are the cutting process parameters, tool variables, workpiece variables, and the dynamic conditions of the cutting system. Based on the input data, *SurfGM* is capable of simulating the tool locus, virtual surface waviness, sectional surface roughness profile as well as the surface profile of a turned surface. It is beneficial in calculating most of the surface roughness parameters.

The *SurfGM* consists of three modules: data input module, preview and simulation module and roughness parameters calculation module. Data input module, Fig. 4, is built for easy to edit and to change machining variables, tool variables, workpiece variables and machine-tool-workpiece structural variables. Machining variables are feed, spindle speed, depth of cut and coolant type. Tool variables are tool nose radius, tool geometry (side and back rake angles, side and end cutting edge angles, side and relief angles and inclination angle), tool materials and tool wear (low, medium and high). Workpiece variables are workpiece diameter and length, and workpiece materials. Machine-tool-workpiece variables are spindle, tool and workpiece structure. It is possible to simulate surface profile in case of both ideal surfaces and the generated surfaces based on random and dynamic machine tool vibrations.

The second module is the surface profile preview, *SurfPreview*, which was build to preview the generated surface profile according to the input data, Fig. 5. The preview area displays the generated surface of the tool path for one sample length. The path number, last path and all paths can be displayed on user request. The user can select the appropriate cut of length, number of sampling length and sampling number. The Auto Preview checkbox is used to perform automatic execution of the roughness profile when the processing parameters are changed by the user. The lower graph shows the resulting surface profile after applying least square mean line. The upper and lower graphs are updated according to simulation method selections which are *Ideal Surface*, *Random Vibration* and *Dynamic* pushbuttons selection. The ideal surface is the resulting profile due to feed and tool nose radius. The random vibration generates a profile that depends on a random tool vibration. The dynamic pushbutton uses the machine-tool-workpiece simulation to generate the predicted surface profile.



Feed (f) 0.05 mm/rev
Spindle speed (n) 355 rev/min
Depth of cut (dc) 0.5 mm
Coolant Dry

Tool nose radius (r) 1.2 mm

Side rake 12 ° Back rake 12 °
Side cutting edge 45 ° End cutting edge 75 °
Side relief 10 ° End relief 10 °
Inclination 5 °

Tool type Carbide
Tool material Cemented Carbide

● Low ○ Medium ○ High

Workpiece diameter (D) 36 mm
Workpiece length (L) 50 mm
Workpiece material Ferrous material
Workpiece grade St 42

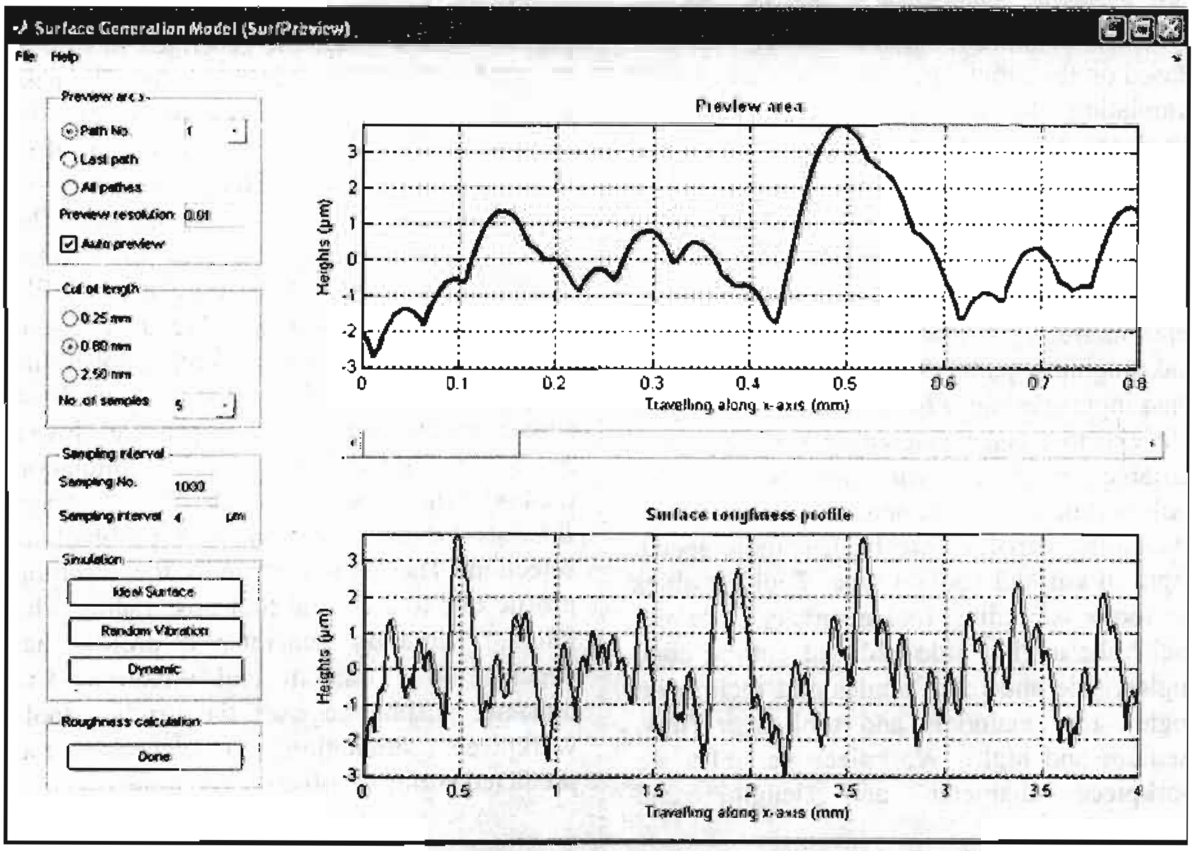
Mass (ms) 34 kg
Stiffness (Ks) 3634500000 N/m
Damping (Cs) 43071.91 N s/m

Mass (mt) 27 kg
Stiffness (Kt) 100 N/m
Damping (Ct) 178.5 N s/m

Mass (mw) 0.39697 kg
Stiffness (Kw) 241900000 N/m
Damping (Cw) 261 N s/m

Damping factor 0.5 N s/m

Fig. 4. Surface Generation Model *(SurfGM)*: Data input module.



● Path No. 1
○ Last path
○ All pathes
Preview resolution 0.01
☑ Auto preview

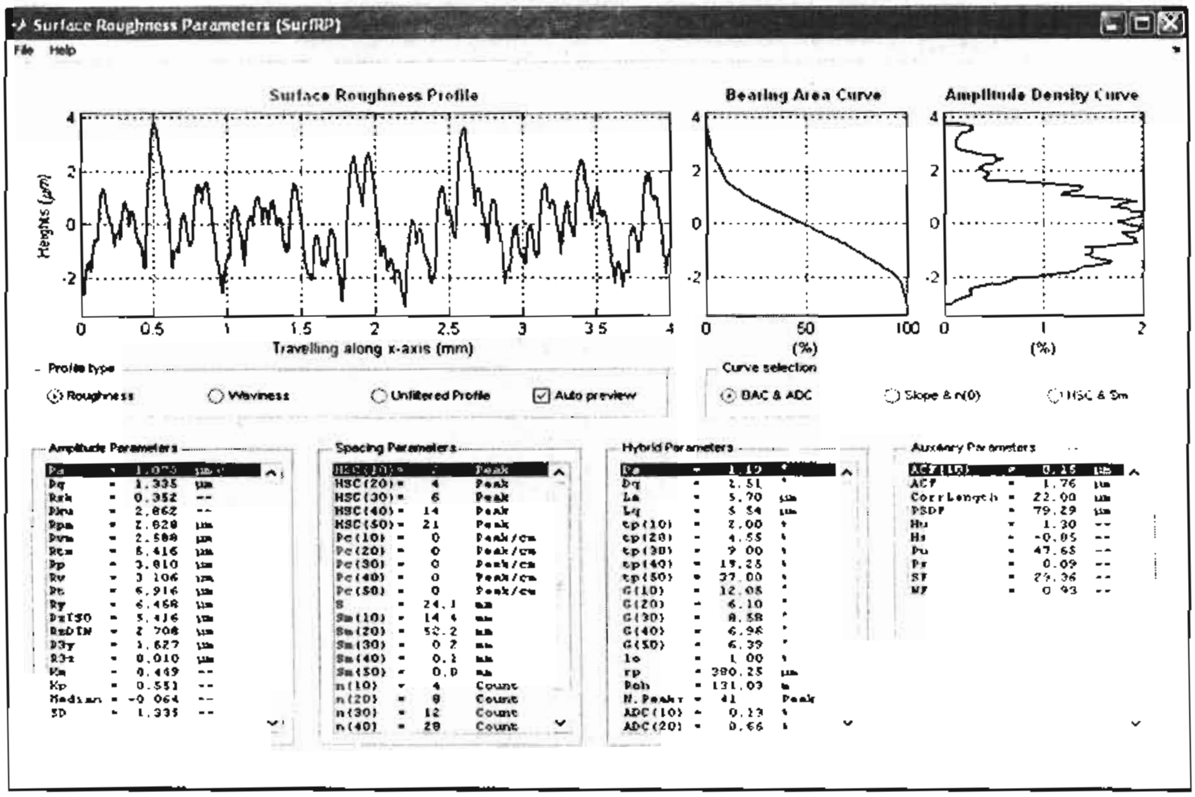
○ 0.25 mm
● 0.80 mm
○ 2.50 mm
No. of samples 5

Sampling No. 1000
Sampling interval 4 µm

Fig. 5. Surface Generation Model: Preview and simulation module *(SurfPreview)*.

The roughness parameters of the executed profile can be calculated by clicking the Done button, which displays the third module as shown in Fig. 6.

The third module is the surface roughness parameters, *SurfRP*, which was built to display surface profile, bearing area curve, amplitude density curve, slope curve, number of intersection curve, high spot count curve, mean spacing at the mean line curve and the calculated roughness parameters. The calculated parameters are: Amplitude, spacing, hybrid and auxiliary surface roughness parameters.



Profile type: ● Roughness ○ Waviness ○ Unfiltered Profile ☑ Auto preview

Curve selection: ● BAC & ADC

Amplitude Parameters

```
Ra     =  1.075  µm
Rq     =  1.335  µm
Rsk    =  0.352  --
Rku    =  2.862  --
Rpm    =  2.620  µm
Rvm    =  2.508  µm
Rtm    =  5.416  µm
Rp     =  3.810  µm
Rv     =  3.106  µm
Rt     =  6.916  µm
Ry     =  6.468  µm
RzISO  =  5.416  µm
RzDIN  =  2.708  µm
R3y    =  1.627  µm
R3z    =  0.010  µm
Km     =  0.449  --
Kp     =  0.551  --
Median = -0.064  --
SD     =  1.335  --
```

Spacing Parameters

```
HSC(10) =  2    Peak
HSC(20) =  4    Peak
HSC(30) =  6    Peak
HSC(40) = 14    Peak
HSC(50) = 21    Peak
Pc(10)  =  0    Peak/cm
Pc(20)  =  0    Peak/cm
Pc(30)  =  0    Peak/cm
Pc(40)  =  0    Peak/cm
Pc(50)  =  0    Peak/cm
S       = 24.1  µm
Sm(10)  = 14.4  µm
Sm(20)  = 52.2  µm
Sm(30)  =  0.2  µm
Sm(40)  =  0.1  µm
Sm(50)  =  0.0  µm
n(10)   =  4    Count
n(20)   =  8    Count
n(30)   = 12    Count
n(40)   = 28    Count
```

Hybrid Parameters

```
Δa      =   1.19  °
Δq      =   2.51  °
λa      =   5.70  µm
λq      =   5.54  µm
tp(10)  =   2.00  %
tp(20)  =   4.55  %
tp(30)  =   9.00  %
tp(40)  =  15.25  %
tp(50)  =  37.00  %
G(10)   =  12.05  °
G(20)   =   6.10  °
G(30)   =   8.58  °
G(40)   =   6.96  °
G(50)   =   6.39  °
lo      =   1.00  %
rp      = 380.25  µm
Roh     = 131.09  m
N.Peaks =  41     Peak
ADC(10) =   0.13  %
ADC(20) =   0.66  %
```

Auxiliary Parameters

```
ACF(10)     =  0.15  µm
ACF         =  1.76  µm
Corr Length = 22.00  µm
PSDF        = 79.29  µm
Hu          =  1.30  --
Hs          = -0.05  --
Pu          = 47.65  --
Pr          =  0.09  --
SF          = 23.36  --
MF          =  0.93  --
```

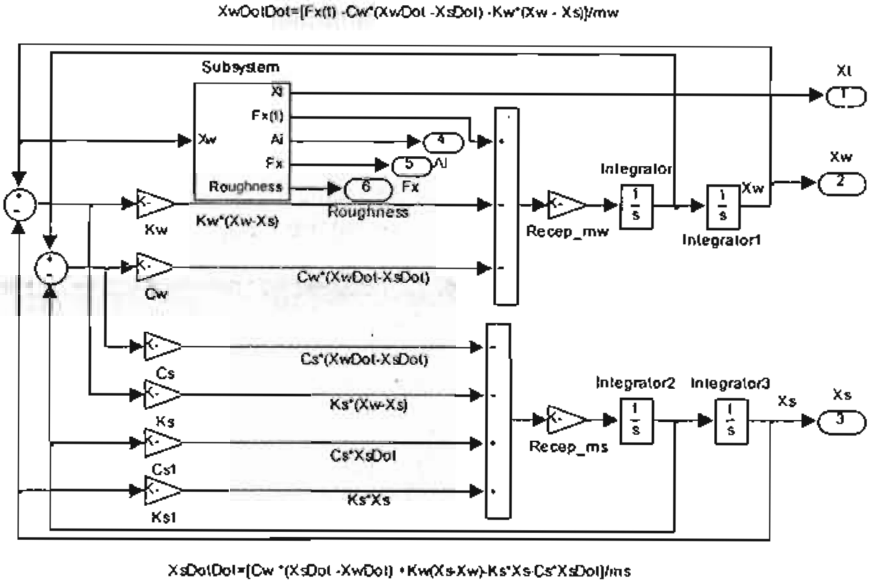
Fig. 6. Surface Generation Model: Surface roughness parameters module *(SurfRP)*.

4. Experimental Verification

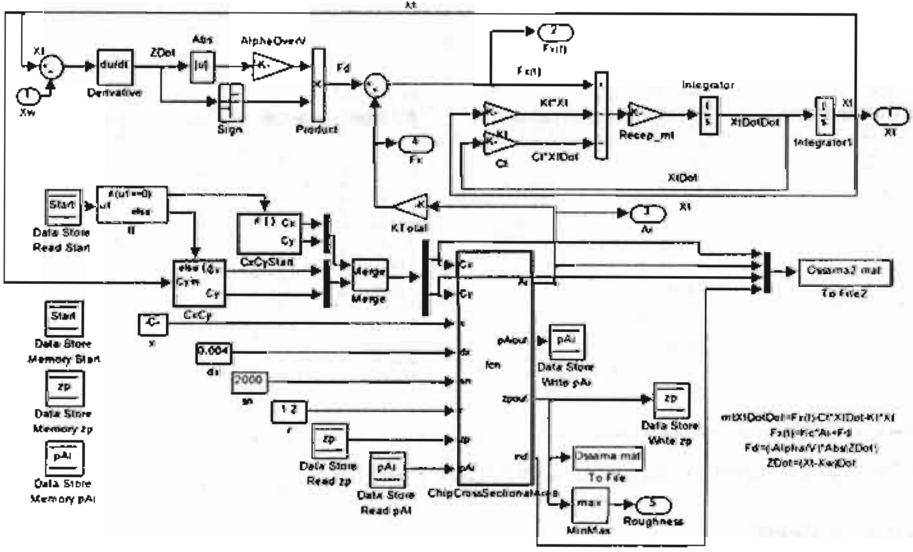
To verify the surface generation modeling of dynamic cutting process and tool geometry, a series of turning experiments for various cutting configurations and process parameters were performed using a turning machine. Surface roughness was measured and two-dimensional roughness parameters were calculated. The average of three measurements was calculated for both predicted and measured roughness.

A throwaway cemented carbide inserts were used in the experiment. The inserts have a tool nose radius of 0.4 mm and a side cutting edge angle of $\chi = 45^\circ$. The workpiece material was free cutting steel having $\sigma_{yield\,(min)} = 225$ MPa, $\sigma_{Ultimate} = 450$ MPa, C = 0.13%, Mn = 1.2%, P = 0.10%, and S = 0.25%. The depth of cut was chosen to be 0.5 mm in the experiments. The test conditions are given in Table 1.

Figures 8-10 show a comparison of the predicted and measured surface roughness for cutting tests. Fig. 8. shows the predicted and measured surface profile for workpiece diameter = 36 mm, Fig. 9. shows the predicted and measured surface profile for workpiece diameter = 30 mm, and Fig. 10. shows the predicted and measured surface profile for workpiece diameter = 24 mm.



(a) Main Simulink model



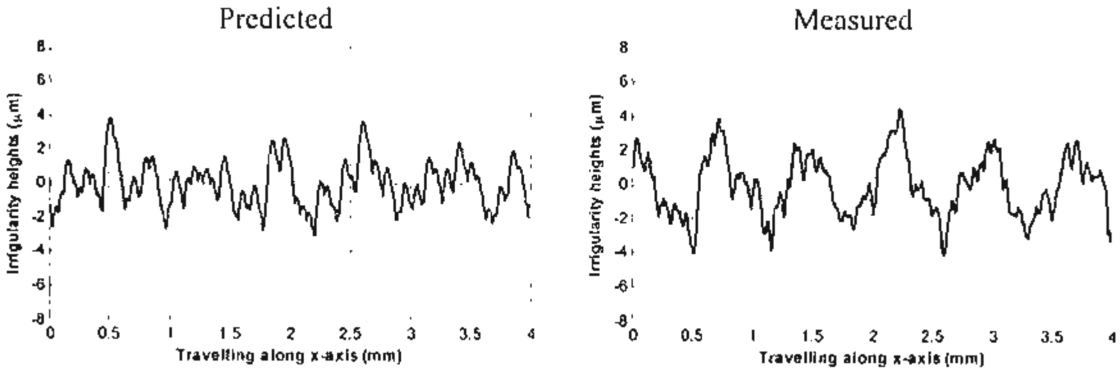
(b) Subsystem Simulink model

Fig. 7. Matlab Simulink model of the dynamic system.

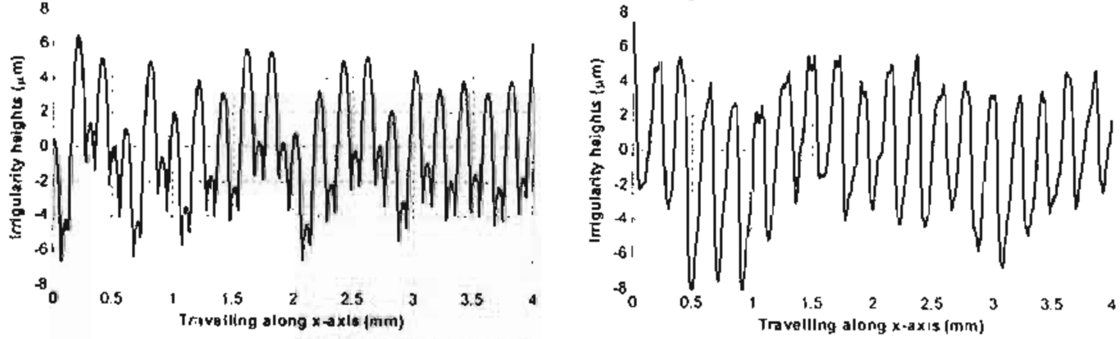
Table 1 Cutting conditions in the turning experiment.

No.	Feed (*f*), mm/rev	Rotational speed, rev/min	Workpiece diameter, mm
1	0.05	355	36
2	0.20	355	36
3	0.05	710	36
4	0.20	710	36
5	0.05	355	30
6	0.20	355	30
7	0.05	710	30
8	0.20	710	30
9	0.05	355	24
10	0.20	355	24
11	0.05	710	24
12	0.20	710	24

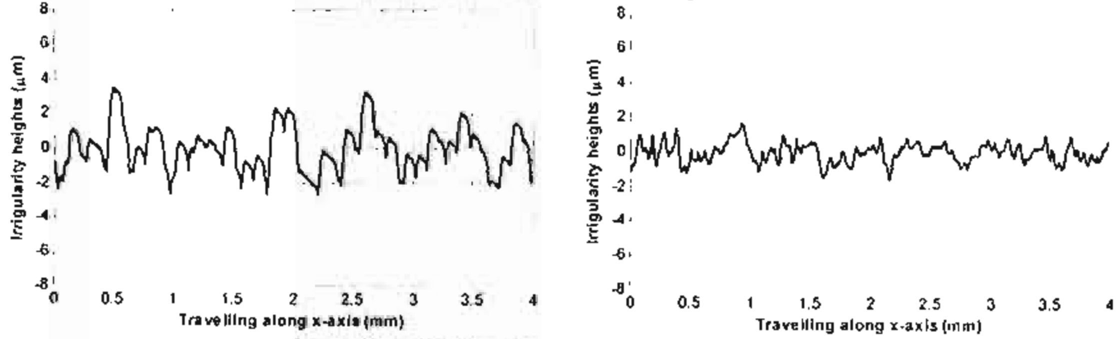
It is obvious that the predicted surface profile is closely matched by that of the measured ones. Tables 2-4 list the means of the predicted and measured roughness parameters and its percentage errors. Percentage errors are calculated from the percentage of the prediction errors divided by the mean of measured roughness parameters. The maximum percentage prediction error is found to be less than 20% for all the tested cases.



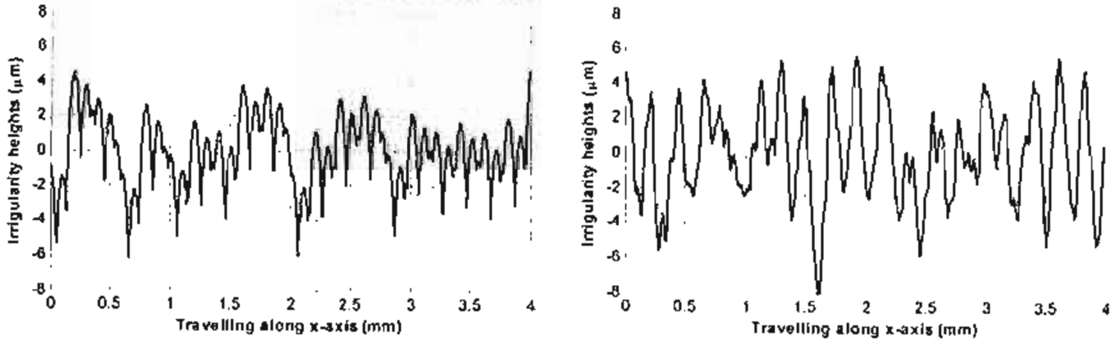
(a) Feed = 0.05 mm/rev and rotational speed = 355 rev/min



(b) Feed = 0.20 mm/rev and rotational speed = 355 rev/min

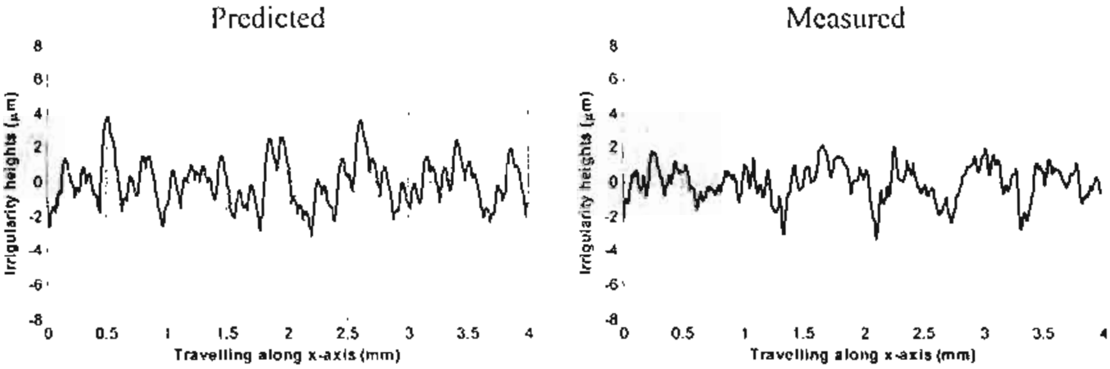


(c) Feed = 0.05 mm/rev and rotational speed = 710 rev/min

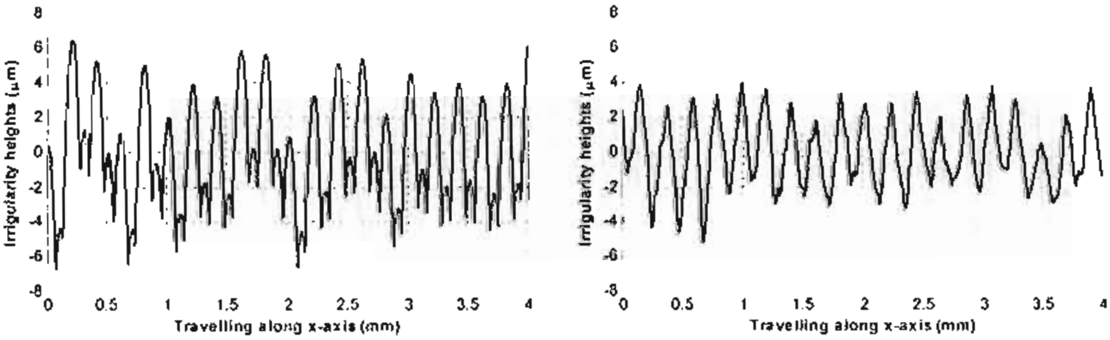


(d) Feed = 0.20 mm/rev and rotational speed = 710 rev/min

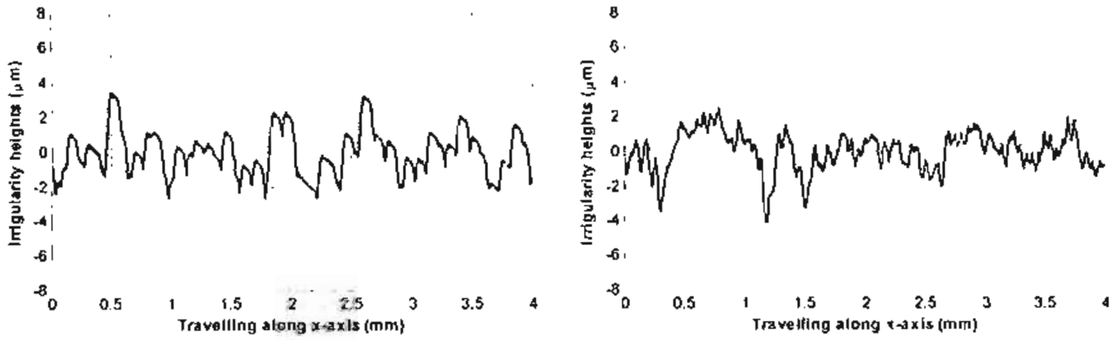
Fig. 8. Predicted and measured surface profile at $d_c = 0.5$ mm, $\chi = 45^o$, $r = 1.2$ mm and workpiece diameter = 36 mm.



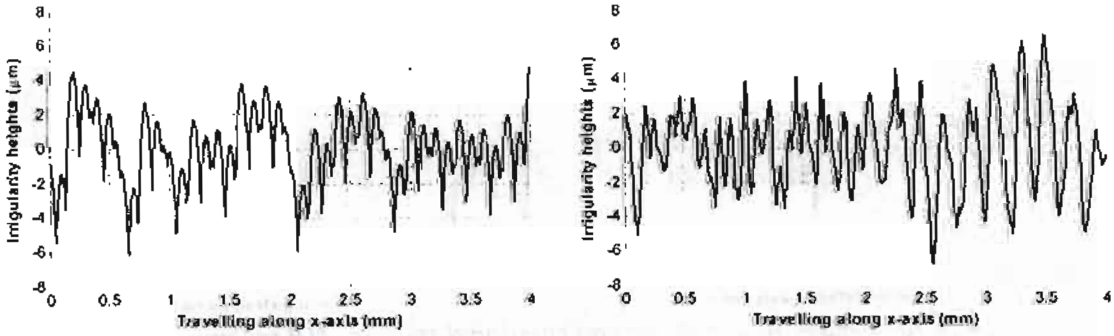
(a) Feed = 0.05 mm/rev and rotational speed = 355 rev/min



(b) Feed = 0.20 mm/rev and rotational speed = 355 rev/min

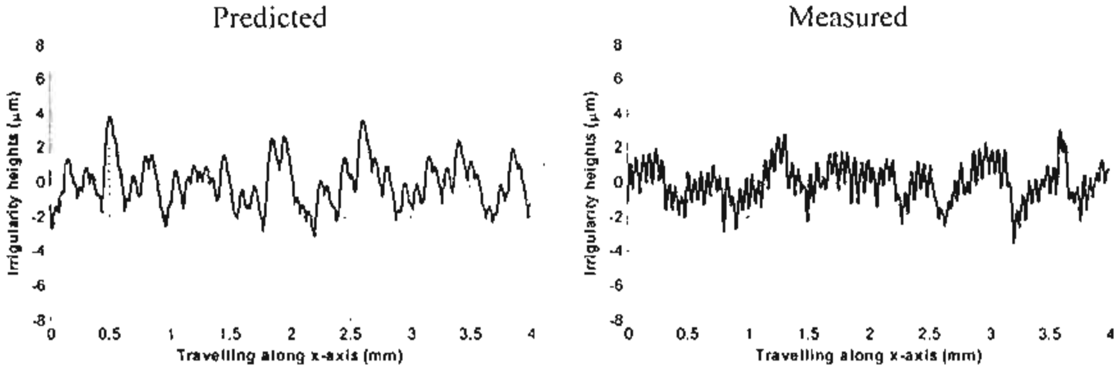


(c) Feed = 0.05 mm/rev and rotational speed = 710 rev/min

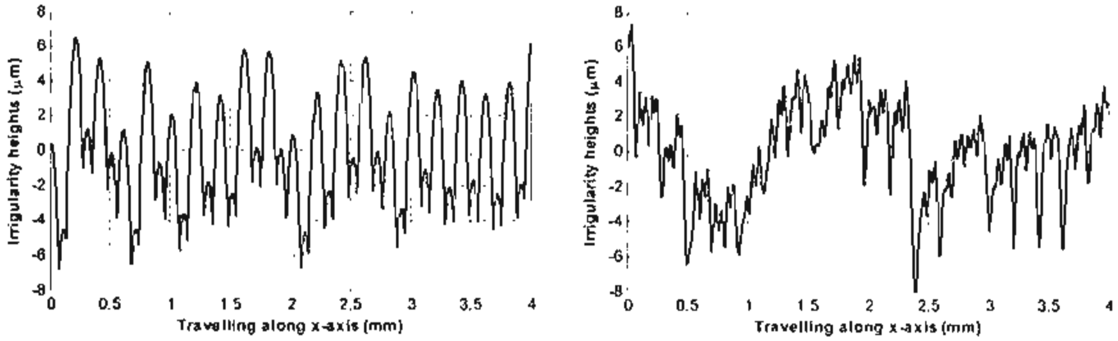


(d) Feed = 0.20 mm/rev and rotational speed = 710 rev/min

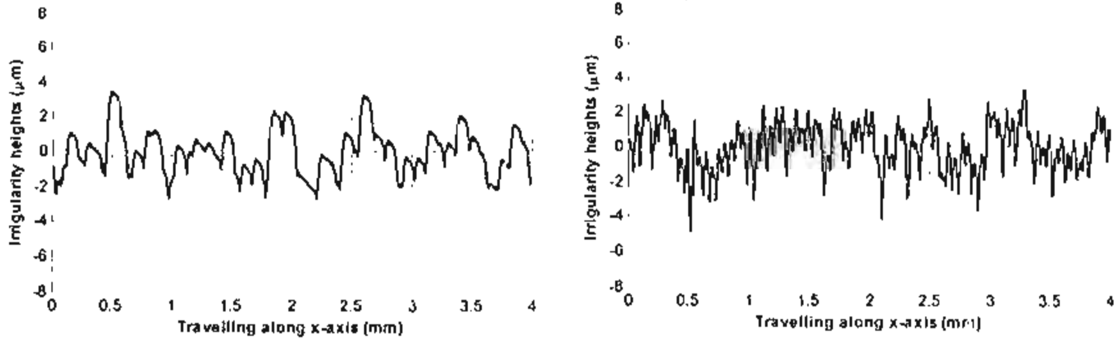
Fig. 9. Predicted and measured surface profile at $d_c = 0.5$ mm, $\chi = 45^0$, $r = 1.2$ mm and workpiece diameter = 30 mm.



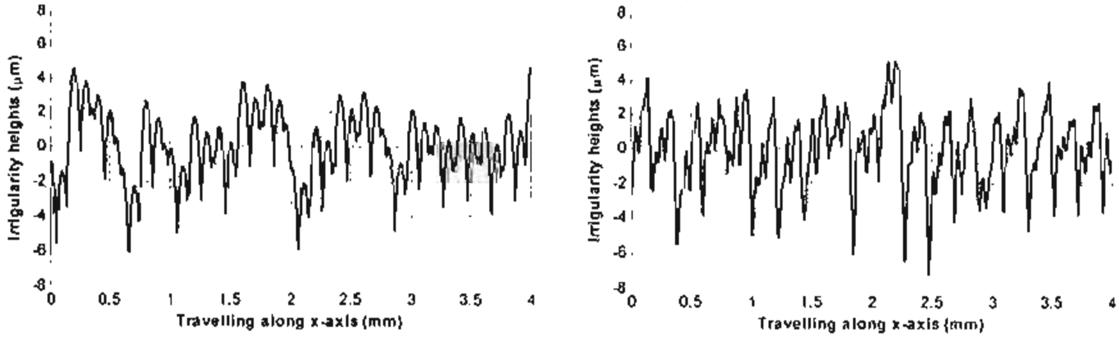
(a) Feed = 0.05 mm/rev and rotational speed = 355 rev/min



(b) Feed = 0.20 mm/rev and rotational speed = 355 rev/min



(c) Feed = 0.05 mm/rev and rotational speed = 710 rev/min



(d) Feed = 0.20 mm/rev and rotational speed = 710 rev/min

Fig. 10. Predicted and measured surface profile at d_c = 0.5 mm, χ = 45°, r = 1.2 mm and workpiece diameter = 24 mm.

Table 2 Predicted and measured surface roughness parameters and their percentage errors for workpiece diameter, $D = 36$ mm.

Roughness parameters	Rotational speed = 355 rev/min						Rotational speed = 710 rev/min					
	Feed = 0.05 mm/rev			Feed = 0.20 mm/rev			Feed = 0.05 mm/rev			Feed = 0.20 mm/rev		
	Mean of predicted roughness	Mean of measured roughness	Error %	Mean of predicted roughness	Mean of measured roughness	Error %	Mean of predicted roughness	Mean of measured roughness	Error %	Mean of predicted roughness	Mean of measured roughness	Error %
R_a	1.08	1.12	4.4	2.49	2.66	6.6	1.03	1.02	1.3	1.60	1.90	18.8
R_q	1.33	1.43	7.0	2.97	3.27	10.0	1.29	1.29	0.3	1.99	2.21	11.1
R_{ku}	2.87	2.32	19.2	2.13	2.16	1.8	2.87	3.39	18.4	2.84	2.53	11.0
R_z	5.40	5.66	4.8	11.49	12.02	4.6	4.91	5.79	18.0	9.05	10.13	12.0
R_t	6.93	6.52	6.0	13.10	15.01	14.6	6.20	7.38	19.0	10.94	12.80	16.9
R_v	6.45	6.17	4.3	13.10	13.98	6.7	5.87	6.80	15.8	10.76	12.53	16.5
l_o	1.000	1.001	0.1	1.000	1.005	0.0	1.000	1.003	0.4	1.000	1.004	0.4

Table 3 Predicted and measured surface roughness parameters and their percentage errors for workpiece diameter, $D = 30$ mm.

Roughness parameters	Rotational speed = 355 rev/min						Rotational speed = 710 rev/min					
	Feed = 0.05 mm/rev			Feed = 0.20 mm/rev			Feed = 0.05 mm/rev			Feed = 0.20 mm/rev		
	Mean of predicted roughness	Mean of measured roughness	Error %	Mean of predicted roughness	Mean of measured roughness	Error %	Mean of predicted roughness	Mean of measured roughness	Error %	Mean of predicted roughness	Mean of measured roughness	Error %
R_a	1.08	0.98	9.4	2.52	2.04	19.0	1.03	1.04	1.0	1.60	1.66	3.9
R_q	1.34	1.19	10.6	3.00	2.43	19.0	1.29	1.33	3.2	1.99	2.08	4.5
R_{ku}	2.87	2.99	4.5	2.11	1.95	7.6	2.86	3.20	11.9	2.83	2.90	2.5
R_z	5.40	4.51	16.5	11.55	9.87	14.5	4.91	5.20	6.0	9.05	8.48	6.3
R_t	6.93	6.98	0.7	13.17	11.42	13.3	6.20	6.94	11.9	10.90	11.01	1.0
R_v	6.46	6.98	8.2	13.17	11.41	13.3	5.87	6.63	13.0	10.71	10.45	2.4
l_o	1.001	1.001	0.0	1.006	1.002	0.3	1.007	1.011	0.4	1.008	1.004	0.4

Table 4 Predicted and measured surface roughness parameters and their percentage errors for workpiece diameter, $D = 24$ mm.

Roughness parameters	Rotational speed = 355 rev/min						Rotational speed = 710 rev/min					
	Feed = 0.05 mm/rev			Feed = 0.20 mm/rev			Feed = 0.05 mm/rev			Feed = 0.20 mm/rev		
	Mean of predicted roughness	Mean of measured roughness	Error %	Mean of predicted roughness	Mean of measured roughness	Error %	Mean of predicted roughness	Mean of measured roughness	Error %	Mean of predicted roughness	Mean of measured roughness	Error %
R_a	1.08	1.00	7.6	2.56	2.27	11.4	1.03	1.12	8.8	1.60	1.72	7.2
R_q	1.34	1.26	6.0	3.03	2.81	7.2	1.29	1.38	6.6	1.99	2.18	9.2
R_{ku}	2.87	3.40	18.5	2.10	2.31	10.3	2.86	2.85	0.5	2.83	3.17	12.2
R_z	5.41	5.85	8.2	11.62	11.39	1.9	4.91	5.86	19.4	9.06	9.74	7.5
R_t	6.93	8.16	17.8	13.26	15.47	16.6	6.21	6.38	2.7	10.85	12.43	14.6
R_v	6.49	7.52	15.8	13.26	13.75	3.6	5.87	6.55	11.7	10.65	11.63	9.3
l_o	1.001	1.004	0.3	1.006	1.005	0.0	1.007	1.005	0.2	1.008	1.007	0.1

5 Conclusions

In this paper, a predictive surface roughness model was presented for the simulation and analysis of the dynamic cutting process in turning. The surface roughness was determined by using a predictive machining theory, which predicts the surface roughness from the input data of workpiece material properties, the tool geometry, the cutting conditions and machine-tool-workpiece structure. The instantaneous undeformed chip thickness was modeled to include the dynamic modulations caused by the tool vibrations so that the dynamic regeneration effect was taken into account.

A Simulink model was built to solve the differential equation governing the dynamics of turning system for accurate solutions. Turning experiments under a wide range of cutting conditions were performed and results were presented in the verification of the analytical model. Comparisons between the simulated and experimental results have been presented to verify the dynamic model. It was shown that by using the proposed *SurfGM* program, the simulation results agreed to a certain extent with the cutting test in the prediction of the cutting process. The percentage errors between predicted and measured roughness parameters were found to be less than 20%. The method can be used to facilitate the planning of cutting parameters, optimization of tool geometry and on-line diagnostics.

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