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Simulation of cutting process – modeling and applications

Wojciech Jabłoński
AGH University of Science and Technology
Poland

1. Introduction

Cutting process plays an important role in manufacturing of a large range of products for all types of production (shop, batch and mass production). Hence the constant need of improvement and optimization of process and parameters exists. It can be expressed by two postulates: increasing of efficiency and quality. At present the significant improvement of both factors seems to be impossible without understanding of dynamical basics of cutting process. Thus research and development into realistic mathematical models of cutting process, becomes even more important than previously.
Models become a useful instrument for technologist just after adapting of worked out mathematical equations for adequate technological problems. This stage is usually quite difficult and very important because it determines usefulness of model.
In the chapter dynamical model of cutting process for turning was described. The model denotes two-degree-of freedom tool deflection caused by dynamical cutting force. It considers the main dissipative factors: regenerative effect and process dumping caused by dynamical limit federate. As the result of analysis, the main ranges of potential application were proposed

2. Methodology of cutting process modelling

In cognitive process of complex problem the acceptance of physical model representing the present level of knowledge is very important. The excessive complication of model slightly enlarges labour input and hardware requirements to obtain expected results, thus makes its effective utilization impossible. Hence the compromise between informativness and complication of the model become essential. Mathematical model understood as mathematical description of physical dependences of observed phenomenon is created in the next step. This description can be provided by algebraic equations, ordinary or partial differential equations, differential and integral equations or retarded differential equations. The later are most important for cutting process modelling for which the influence of history of the process on present system state should be considered.
One can affirm that dynamical processes occurring in model do not reflect the real phenomenon, but rather describe the current level of knowledge. Differences between real

process and physical model can be called disturbances. Disturbances are understood as known or unknown influence of not large changes of system parameters on the process course. This influence is usually excepted.

The next stage of dynamical modelling is analysis of motion equations of studying system. The method of analysis depends on the type of model equations. For linear differential equations the analytic solutions are searched. But for even simple nonlinear systems there are no accurate solutions, or determining of these solutions is very inconvenient [Hale 1977] In these cases the approximate analytic methods on basis of elementary functions can be applied. It permits the initial orientation due to qualitative and sometimes also quantitative aspect of system dynamics. But mostly the numerical methods definitely predominate for nonlinear systems analysis.

In the last stage of modelling, the parameters for which required dynamical features can be obtained are selected. It is called synthesis and optimization.

Apart from the mentioned above theoretical analysis, the experimental research should be provided. It enables identification of physical model parameters and verification of mathematical model and obtained results. Often the experimental research is provided parallel to the theoretical ones.

The pattern of dynamical process analysis is presented on fig. 1.

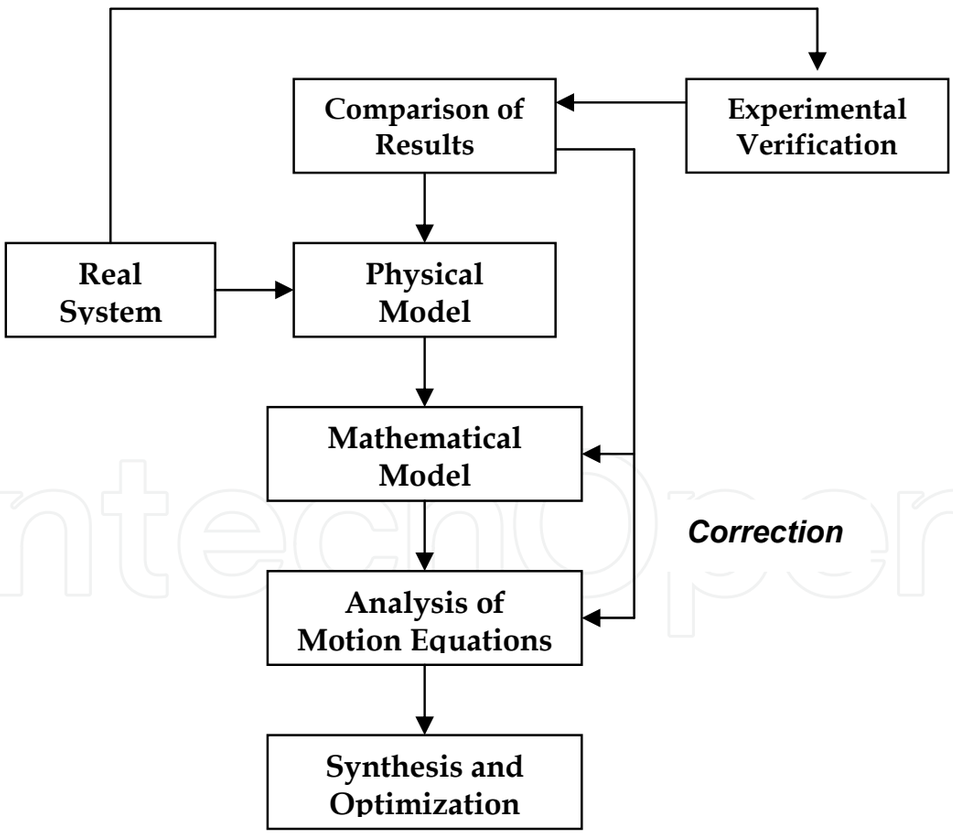


Fig. 1. Methodology of dynamical systems analysis

There are several varieties of models, used depending on the kind of analysed problem. It distinguishes two main classes of physical models:
- structural models, in which the organization is similar to the structure of the analysed system and the pertinence between elements of the model and object appears,
- functional models, which similarity to the object consists in compatibility of the model and object output signals. In case of mechanical systems there are continuous and discrete models. First of them are systems where parameters are distributed in continuous way and they are described by partial differential equations, integral equations or differential and integral equations. Discrete systems one describes by ordinary differential equations and usually they are easier to analyse than continuous ones, thus continuous systems are often approximated by discrete systems. Moreover the linear and nonlinear models are differentiated.

3. Nonlinearities of cutting process

The main reasons of chatter stabilization are two basic nonlinearities of cutting process [Jemielniak & Widota 1988]:
- brakes in cutting process caused by departure of the cutting edge from workpiece,
- increase of cutting force in range of kinetic clearance angle close to zero [Jabłoński 1997].

Departure of the cutting edge from workpiece enabling disappearance of cutting force, can be taken into consideration by defining relation $x_T=x(t-\tau)$ (fig. 2). This value one can describe on the basis of edge trace generated in previous passes (revolutions) on workpiece surface:

$$x_T = \min\{x(t-\tau), a_0 + x(t-2\tau), 2a_0 + x(t-3\tau) \ldots\}$$

where: a_0 – nominal thickness of cut.

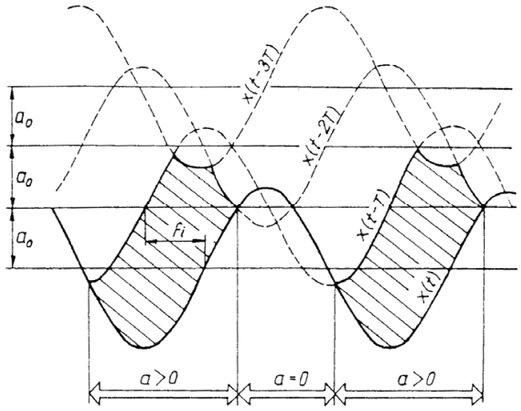


Fig. 2. Traces reflected on a machined surface in following passes (revolutions) [Jemielniak & Widota 1988].

During first revolution existing of x_T parameter in not justified thus it takes value of zero.
Cutting generates vibrations of the tool. These vibrations cause changes of the kinetic clearance angle (fig. 3). While decreasing of α, cutting force increases and cutting process is strongly dumped.

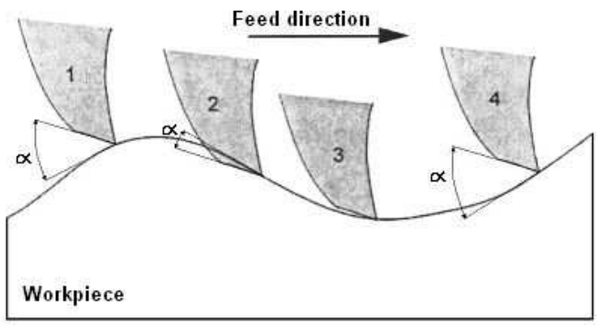


Fig. 3. Dependence of kinetic clearance angle on parameters of movement (vibrations) during cutting [Weck & Altintas 2004].

One of the most important reasons of self-excited vibrations is regenerative effect [Gasiński & Jabłoński 1994]. It enables taking into consideration the state of process in the present and previous moment (while turning – revolution), thus considering the history of process. This fact makes the model much more realistic and unfortunately also very complicated.
For the sake of various values of cutting forces, the cutting process is never free from vibrations. Even when the changes of a force are very small they cause waviness of the workpiece surface, as a result of the limited machine tool stiffness. The entrance of a cutting edge into a waved layer (in turning after one revolution of a workpiece) causes dynamical influence on the machine tool. The dynamical changes of the cutting force among other things depend on the modulation of the area of cutting and so, on the active length of the cutting edge and the modulation of the cutting depth [Dmochowski 1981]. The depth of cut value is strongly affected by a phase shift between the previously made waviness and the current dislocation in the cutting point (fig. 4). On the other hand, amplitude depends on dumping in the process – machine tool system.

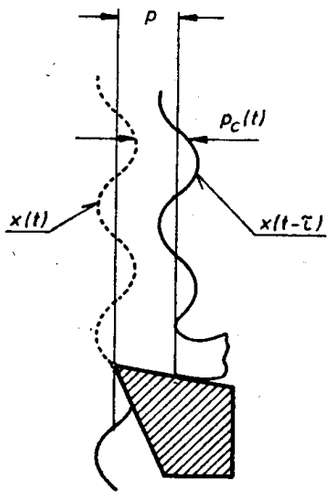


Fig. 4. Section of the cut – regenerative effect [Dmochowski 1981]

4. Known models of cutting process for turning

First nonlinear mathematical one-degree-of-freedom model was published by Arnold in 1946 [Arnold]. Proposed equation had the form:

$$M\ddot{x}(t) - [A + Bx - \varphi(x)]\dot{x}(t) + F'x(t) = K$$

where:

M, A, B, F', K - constants,
$\varphi(x)$ - closer indefinite function, representing dependence of system dumping on tool movement $x(t)$.

In 1988 Grabec proposed two-degree-of-freedom model, for which the chaotic behaviour was observed [Grabec 1988] (fig. 5).

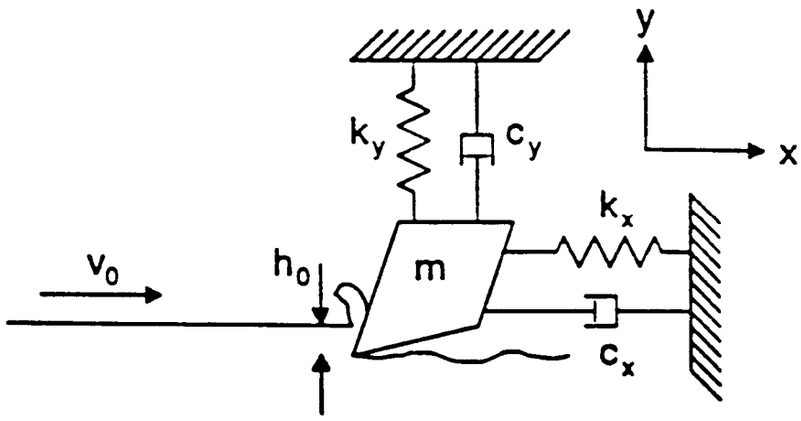


Fig. 5. Diagram of the system for chaotic behaviour model proposed by Grabec [Grabec 1988].

The equations describing

$$m\ddot{x}(t) + c_x\dot{x}(t) + k_x x(t) = F_{x0}\left(\frac{h_0 - y(t)}{\bar{h}_0}\right)\left[C_1\left(\frac{v_0 - \dot{x}(t)}{\bar{v}_0} - 1\right)^2 + 1\right]\aleph\left(\frac{h_0 - y(t)}{\bar{h}_0}\right)\aleph\left(\frac{v_0 - \dot{x}(t)}{\bar{v}_0}\right)$$

$$m\ddot{y}(t) + c_y\dot{y}(t) + k_x x(t) = K_0 F_{x0}\left(\frac{h_0 - y(t)}{\bar{h}_0}\right)\left[C_1\left(\frac{v_0 - \dot{x}(t)}{\bar{v}_0} - 1\right)^2 + 1\right]$$

$$\times\left[C_2\left(\frac{v_0 - \dot{x}(t) - R\ \dot{y}(t)}{\bar{v}_0} - 1\right)^2 + 1\right]\left[C_3\left(\frac{h_0 - y(t)}{\bar{h}_0} - 1\right)^2 + 1\right]\mathrm{sign}\left(\frac{v_0 - \dot{x}(t) - R\ \dot{y}(t)}{\bar{v}_0}\right)$$

$$\times\aleph\left(\frac{h_0 - y(t)}{\bar{h}_0}\right)\aleph\left(\frac{v_0 - \dot{x}(t)}{\bar{v}_0}\right)$$

Where:

$\bar{v}_0, \bar{h}_0, C_1, C_2, C_3 C_4$ - constants,
$\aleph()$ - step function

The chaotic behaviour of system was obtained thanks to some assumptions.

The relatively simple one-degree-of-freedom model was proposed in 1989 by Hamdan and Bayoumi [Hamdan & Bayoumi 1989]. It enables to take into consideration friction effects on flank face and rake face depending on cutting speed:

$$m\ddot{y}(t)+\left[C-C_e\left(\frac{1}{1-\dot{y}(t)/v_0}\right)\right]\dot{y}(t)+(k-k_e)(t)=0$$

where:

m, C, C_e, k, k_e - constants,

v_0 - nominal cutting speed.

In 1991 Lin and Weng presented two-degree-of-freedom model [Lin & Weng 1991]:

$$\ddot{x}(t)+2\xi\dot{x}(t)+x(t)=-dF_x$$

$$\ddot{y}(t)+2l_1\xi\dot{y}(t)+l_2x(t)=-d\,F_y$$

where components of cutting force take form of cubic polynomials of variables $x(t)$, $x(t-\tau)$, $y(t)$, $y(t-\tau)$. Additionally the model enables potential possibility of departure of the cutting edge from workpiece.

Even more complicated model were proposed in 1992 by Berger, Rokini and Minis [Berger et al. 1992]. In this case the state equations take form:

$$\begin{aligned}
&\dot{x}_1(t)=v_1(t)\\
&\dot{x}_2(t)=v_2(t)\\
&\dot{v}_1(t)=-a_8x_1(t)-a_7v_1(t)+a_1x_1(t-\tau)+(x_1(t)-x_1(t-\tau))\\
&\left[a_3(v_2(t)-v_2(t-\tau))-a_2(v_1(t)-v_1(t-\tau))\right]-a_{11}{v_1}^3(t)\\
&\dot{v}_2(t)=-a_4x_1(t)-a_{10}x_2(t)-a_9v_2(t)+a_4x_1(t-\tau)+(x_1(t)-x_1(t-\tau))\\
&\left[a_6(v_2(t)-v_2(t-\tau))-a_5(v_1(t)-v_1(t-\tau))\right]-a_{12}{v_2}^3(t)
\end{aligned}$$

where constants a_k (for k=1, 2, 3, ..., 12) depend on concrete cutting conditions and τ is time of one workpiece revolution.

In 1997 in Moon and Johnson in their book presented the model of regenerative effect [Moon & Johnson 1997].

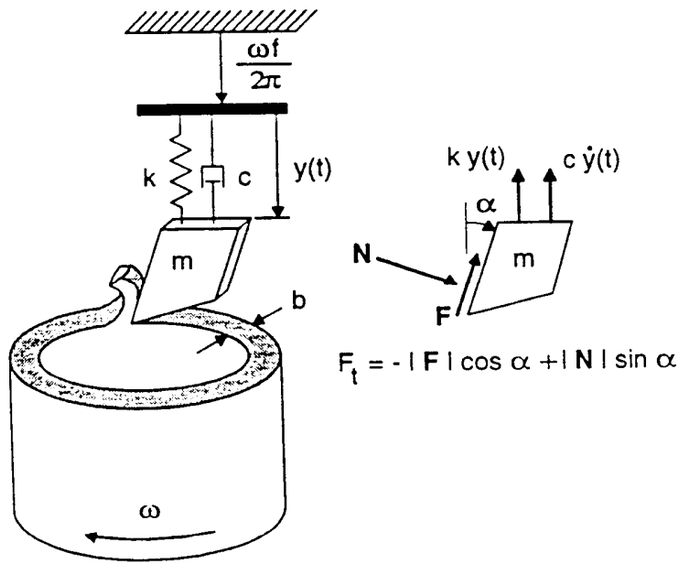


Fig. 6. Diagram of cutting system for simplified one-degree-of-freedom regenerative effect [Moon & Johnson 1997].

For the coordinate system accepted as on fig. 6 the dynamics of the cutter one can described by equation:

$$m\,\ddot{y}(t) + c\,\dot{y}(t) + k\,y(t) = -F_t\left(f - y(t) - y(t-\tau)\right)$$

where:
m, c, k – mass, dumping and stiffness of tool-workpiece system
Ft – thrust component of cutting force
f – nominal feed
τ – duration of one workpiece revolution (time lag)

Normalizing by following substitutions:

$$\overline{y} = -\frac{F(f)}{k}, \quad x(t) \equiv y(t) - \overline{y} = y(t) - \frac{F(f)}{k}$$

equation takes the form:

$$\ddot{x}(t) + \frac{c}{m}\dot{x}(t) + \frac{k}{m}x(t) = -\frac{1}{m}\left[F_t\left(f + x(t) - x(t-\tau)\right) - F_t(f)\right]$$

Even for assumed the linear dependence of thrust component Ft on thickness of the cut, relation *x(t) - x(t - τ)* must be respected. After expansion of Ft function in Taylor series and taking into consideration only its linear factor, equation … takes form:

$$\ddot{x}(t) + 2\xi\omega_0\dot{x}(t) + {\omega_0}^2 x(t) = -\frac{k_s(f)b}{m}\left(x(t) - x(t-\tau)\right)$$

Where:
b – width of cut, and

$$\omega^2 \equiv \frac{k}{m}, \qquad \xi \equiv \frac{c}{2\sqrt{km}}, \qquad k_s(f) \equiv \frac{F_t'(t)}{b},$$

It is experimentally affirmed that value of F_t component is approximately proportional to the width of cut, thus value *ks(f)* one can assume as regardless of *b*.
The model was built on a basis of quasi-static measurements of F_t force. The results of stability analysis of cutting process are presented on fig. 7. Similar model was proposed by Stépán [Stépán 1989]. He also presented the method of mathematical analysis of this problem.

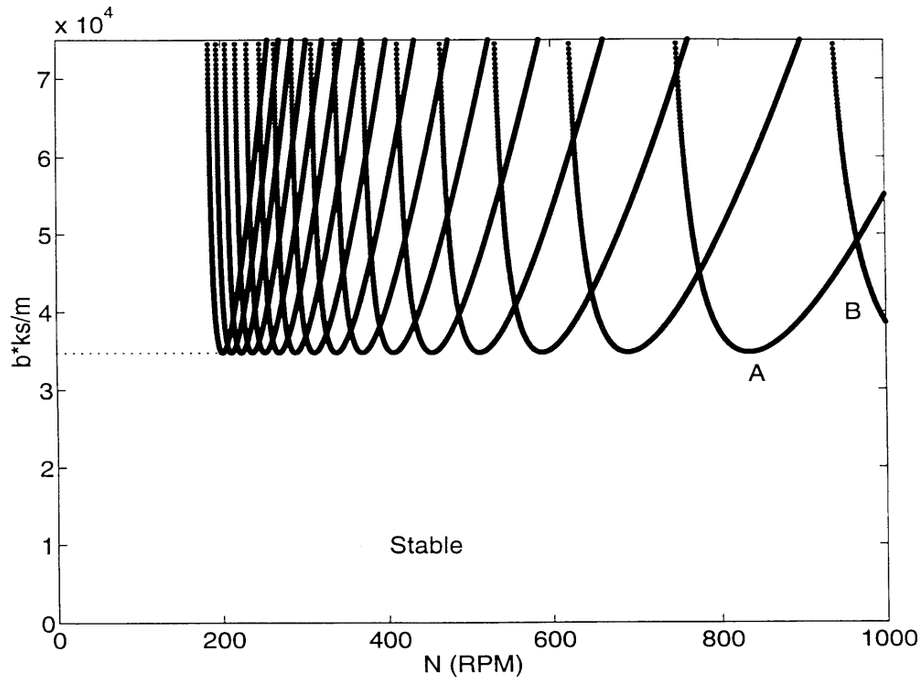


Fig. 7. Graph of stability for a model of regenerative effect. On the vertical axis the factor proportional to section of a cut was marked [Moon & Johnson 1997].

Conclusions for cutting process modelling

All described above model represent different approach to the problem of cutting process analysis and modelling. They are taking into consideration different phenomena recognised as important. Also the number degrees-of-freedom is different. Most models are based on similar assumptions:
- tool is treated as beam vibrating under outside excitement of cutting force components,
- workpiece material is undeformable and homogeneous,
- machine tool is treated as infinitely stiff system except for vibrating elements (mostly tool),
- regenerative effect is the most important dissipative factor.

Analysing of above assumptions, utility for describing a process and expenditures in hardware and time sense, it can express some postulates for new created model:

1) number degrees-of-freedom should be at least two in order to secure the most accurate describing of process,
2) one should take into consideration the basic dissipative factors, especially regenerative effect and increase of cutting force in range of kinetic clearance angle close to zero,
3) model should be constructed in modular way to enable of its easy extension as development of knowledge level,
4) all parameters and variables should be normalised to nondimensional form,
5) one should apply group parameters representing connection between simple parameters, because obtained in this way outcomes concern not only process running in concrete conditions but also all set of conditions described by the same group parameters.

Last year many models of cutting process were worked out, but most of them are made for milling, drilling or grinding process [Chang & Lu 2006, Göloğlu & Arslan 2009, Öktem 2009, Prakasvudhisarn 2009, Routara 2009, Suresh & Venkateswara 2005]. The analysis of turning process is close to the state from the turn of a century. But turning is still one of the most important cutting methods and constant research in this area is justifiable.

5. Nonlinear dynamical model proposed by author

In papers [Gasiński & Jabłoński 1994, Jabłoński 1997, Jabłoński 2004] the mathematical model of cutting process was proposed. It applies to turning with assumption of one- and two-degrees-of-freedom. Model was worked out on basis of models presented above and enables taking into consideration most of the described phenomena except for friction, which is treated as an integral part of the process and not analysed separately.
One of the most important advantages of this model is its modular structure, allowing consideration of the new factors making model more and more realistic.
Current form of model permits three-degrees-of-freedom process description. This way we have got very effective tool for numerical cutting process analysis and simulation.
The main assumption of the model:

- the model concerns turning as a one of the most important cutting methods,
- the only cutter movement is taken into consideration - the other elements of cutting system are treated as infinitely stiff and in the workpiece material as homogeneous,
- the cutter is a beam vibrating under influence of cutting force,
- the main dissipative factors are considered, thus the history of the process (regenerative effect) as well,
- standardization of model variables and parameters permit nondimensional description – the solutions concern many situations described by the same parameters.

The starting point of mathematical model was the experimental equation of cutting force (1) and differential equation of vibrating beam movement.

$$F = C \cdot a_p^{u_g} \cdot f^{u_p}$$

where:
C – cutting process dependent constant, a_p – depth of cut, f – feed, u_p, u_g – empirical exponents,

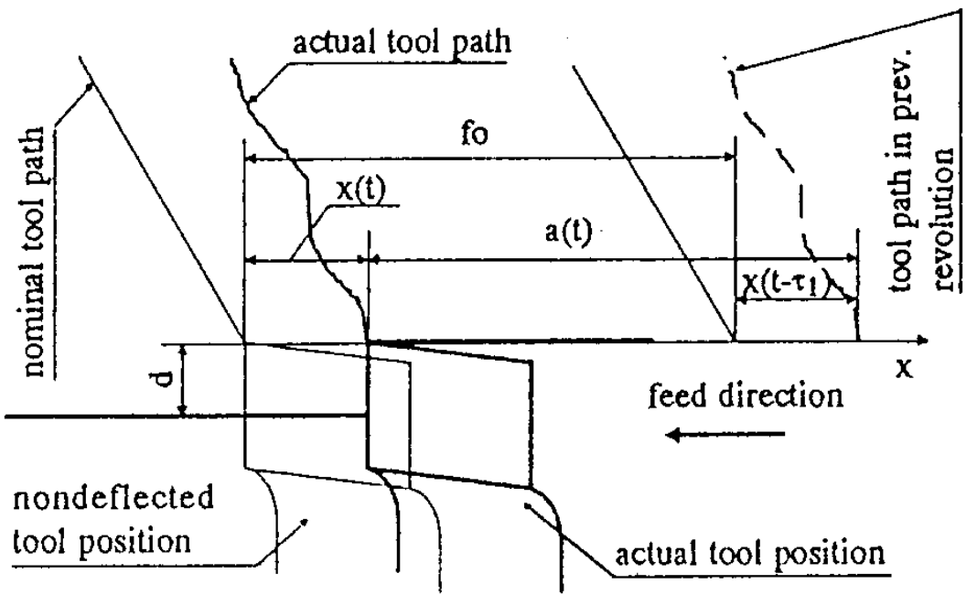


Fig. 8. The tool system while turning [Gasiński & Jabłoński 1994]

Figure 8 presents the physical model of cutter-workpiece system. In the considered example feed and depth of cut are variables, thus a the cutting force equation takes form:

$$F = C \cdot a_p(t)^{u_p} \cdot f(t)^{u_p}$$

The movement equations one can write as:

$$m \cdot \ddot{x} + c_x \cdot \dot{x} + k_x \cdot x = F_p(a_p(t), f(t)) \cdot f_{tl}$$
$$m \cdot \ddot{y} + c_y \cdot \dot{y} + k_y \cdot y = F_c(a_p(t), f(t)) \cdot f_{tl}$$

where:
x – feed direction, y – thrust direction, f_{tl} – process-dependent dumping function of model.

After transforming and normalization to non-dimensional form the model state equations are:

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = \lambda_x \left((1 - \mu y_1(\tau))^v (1 - x_1(\tau) - y_1(\tau) ctg\kappa + x_1(\tau - T) + y_1(\tau - T) ctg\kappa)^w \right) \left(C_1 + \frac{C_2}{\varphi - 1 + x_2 T + y_2 T ctg\kappa} \right) - 2\beta\xi x_2(\tau) - x_1(\tau)$$

$$\dot{y}_1 = y_2$$

$$\dot{y}_2 = \frac{1}{\beta^2} \left(\frac{1}{\varepsilon} \lambda_x \left[(1 - \mu y_1(\tau))^v (1 - x_1(\tau) - y_1(\tau) ctg\kappa + x_1(\tau - T) + y_1(\tau - T) ctg\kappa)^w \right] \right) \cdot \left(C_1 + \frac{C_2}{\varphi - 1 + x_2 T + y_2 T ctg\kappa} - 2\beta\xi y_2(\tau) - y_1(\tau) \right)$$

where the non-dimensional parameters denote:
x_1, y_1 - normalized tool deflection respectively in feed and thrust direction, $x_1 = x/f_o$,
f_o - feed rate, φ - limit feed rate,
λ_x - factor representing the tool flexibility in X axis direction,
T – nondimensional duration of one workpiece revolution (nondimensional time lag), $T = t_1 * \omega_x$, t_1 [s], $\omega_x = 2\pi f_x$ [1/s],
β - ratio of natural circular frequency of the tool vibration to X and Y axis, $\beta = \omega_x / \omega_y$,
μ - shape factor of the cutting chip cross - section, $\mu = f_o / d$,
d - depth of cut, κ - approach angle,
ε - ratio of tool flexibility to X and Y axis (flexibility factor), $\varepsilon = \lambda_x / \lambda_y$,
C_1, C_2 - constants depending on assumed dynamic dumping characteristic; v, w - system dependent constants.

6. Applications of model

6.1. Surface roughness evaluation

Development of the methods and algorithms to calculate the workpiece surface roughness after cutting is one of the main cutting process study directions. It combines the modelling and prediction issues [Feng & Wang 2002]. Most of the models denote the milling operations. Turning process analysis is mostly based on modern quasi-mathematical methods such as neural networks [Karayel 2009]. In fact there are a small number of typical mathematical models of turning process.
Important advantages of proposed model are the time and dynamical characteristics of process, obtained by model simulation. They can be used for modelling of stereometrical condition of turned surface for theoretical, homogeneous material .
The approximate outline of roughness one can permit on basis of discreet (every revolution registered) characteristics of time tool deflection in thrust direction. This direction has the biggest influence on surface roughness parameters. The other directions of tool movements result not directly on machined surface form. The main direction tool vibrations have influence chiefly on actual value of cutting speed and the wave generated by the tool in feed direction is removed in next revolution. Thus their impact is negligible.
Registering the actual tool location in thrust direction every revolution one gets an

information about the position of characteristic points of modelled surface. Joining the points by straight line segments one get the first approximation of roughness outline {fig. 9.).
From the formal point of view the actual location of cutter is superposition of tool deflection in all three directions. The vibrations in main direction displace the characteristic points around circumference of the workpiece. It is necessary to register the continuous series to determine the end of each revolution. Then the actual tool deflection in feed direction should be considered. It causes the movement of the characteristic points along considered roughness outline. Modified in this way set of points insignificantly differs from the previous outline, obtained for the thrust direction only. Influence of vertical tool deflection is negligible. Some of outcomes were presented in papers [Jabłoński 1997, Jabłoński 2004].

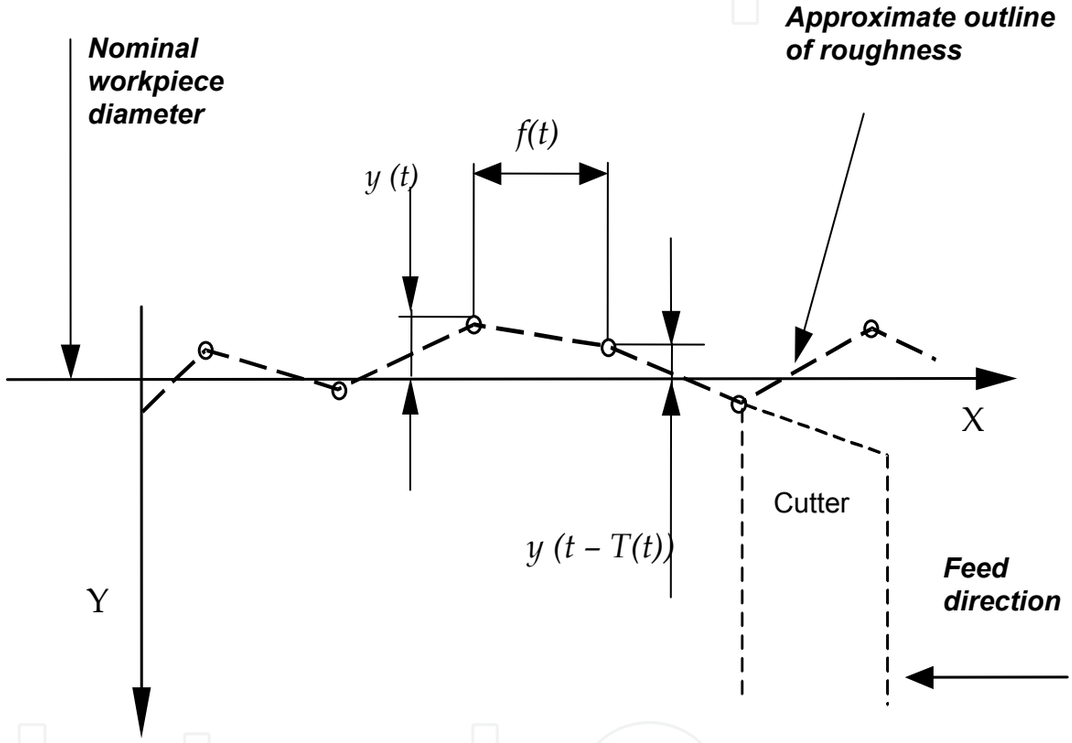


Fig. 9. Theoretical outline of roughness as a result of approximation of points calculated from the stroboscope characteristics: y(t) – tool deflection in thrust direction, tool deflection in previous revolution of workpiece, p(t) – tool movement during one revolution (real value of actual feedrate).

Figure 10 contains the measured R_a and R_q values of turned samples roughness. In figs 11a,b,c the results of modelled roughness was presented. They were obtained on assumption presented on fig. 9, where roughness is treated only as effect of discrete positions of cutter. Roughness values and ratio of R_q/R_a are on similar level. Considering the geometrical tool factors (shape of cutting edge, tool entering angle and corner radius) one can reach more realistic results.

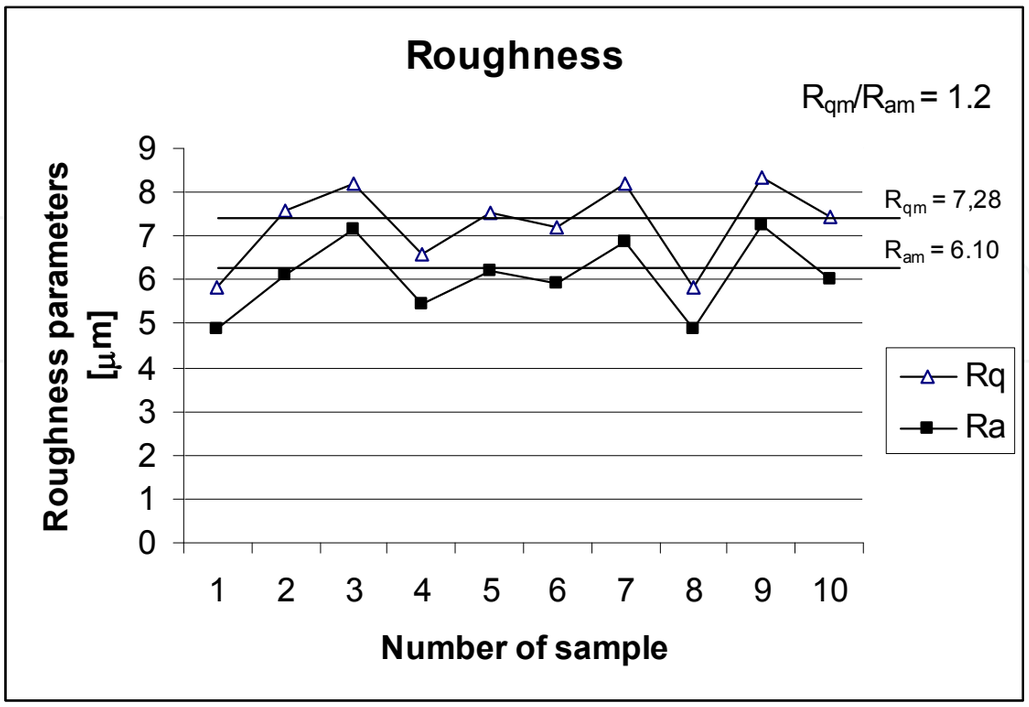


Fig. 10. Measured roughness of turned samples (steel S275, d=30mm, n=560rpm, a_p=3.1mm, f=0.31mm/rev, tool for roughing NNZa (S20)).

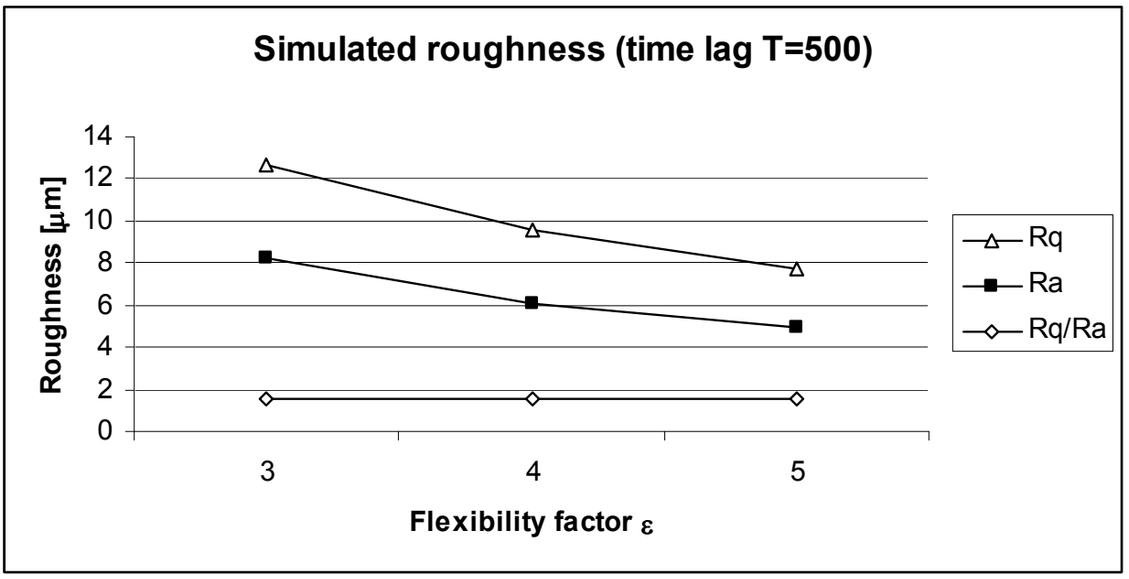


Fig. 11a. Simulated roughness – nondimensional time lag T=500 (φ =5, K=0.02, ξ=0.05, β=4, μ=0.1, λ_x =0.2).

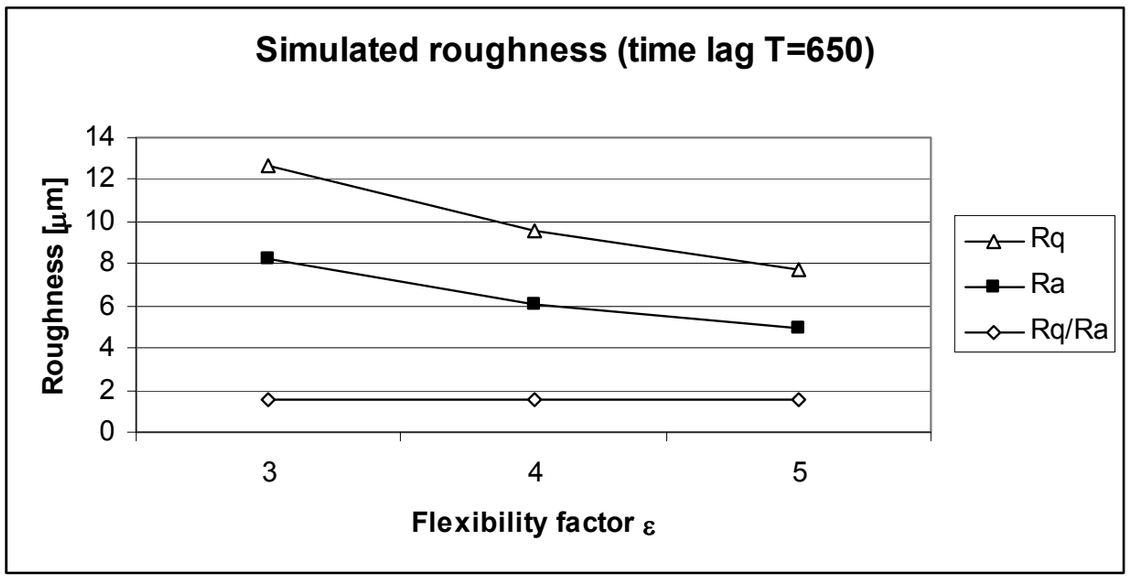


Fig. 11b. Simulated roughness – nondimensional time lag T=650 (φ =5, K=0.02, ξ=0.05, β=4, μ=0.1, λ_x =0.2).

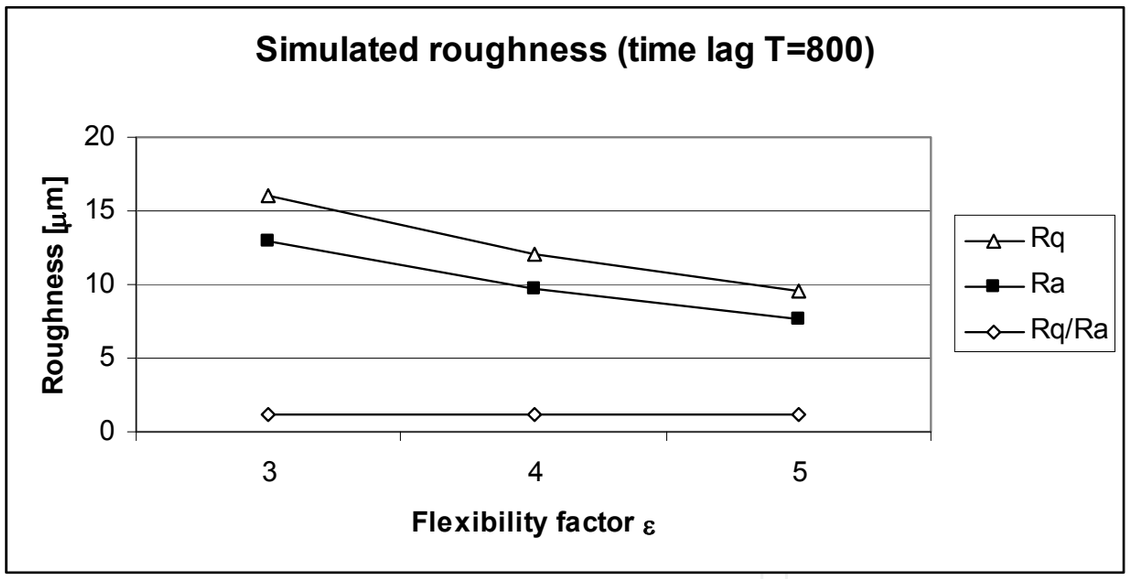


Fig. 11c. Simulated roughness – nondimensional time lag T=800 (φ =5, K=0.02, ξ=0.05, β=4, μ=0.1, λ_x =0.2).

6.2. Application of model for predictive control systems

One of the most important research directions is prediction of the cutting process state. There are many papers considering analysis and prediction of milling process [Kim et al. 2000, Li et al. 2004, Li et al. 2008, Liu et al. 2005, Sadeghi et al. 2003, Yun & Cho 2000]. Turning process is analysed rarely even though most of cutting operations are turning [Li 2001, Lian et al. 2005].

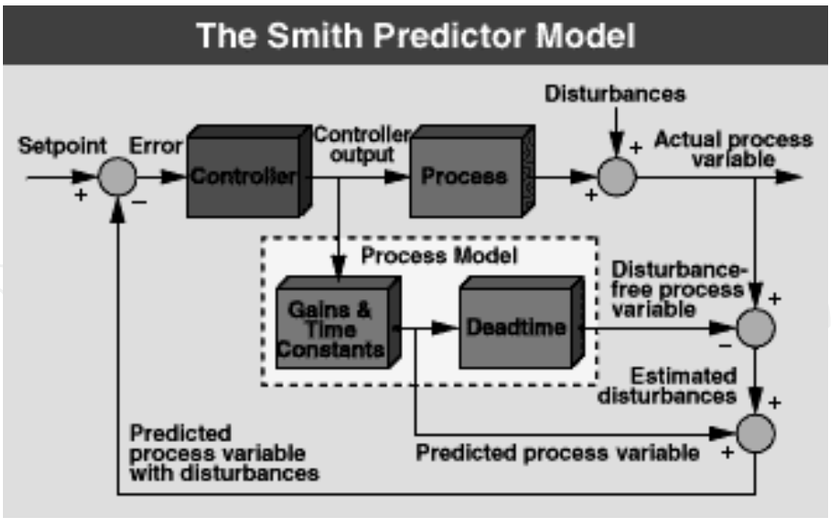


Fig. 12. Diagram of predictive Smith system [VanDoren 1996].

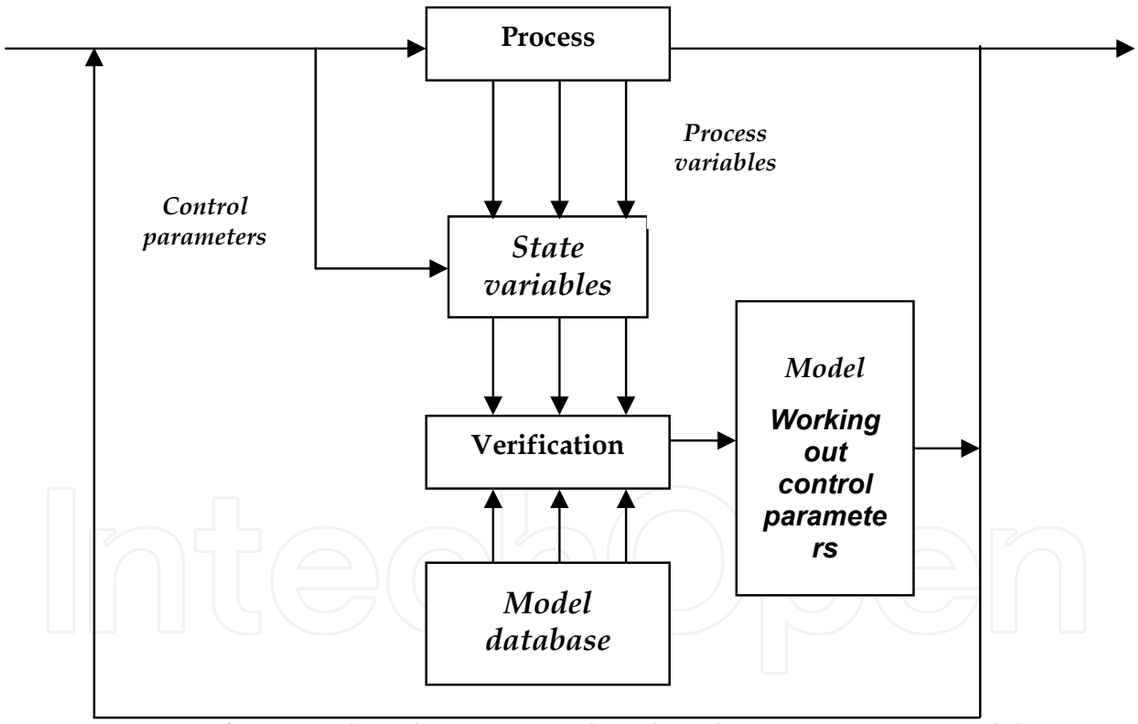


Fig. 13. Diagram of proposed predictive system based on the cutting process model

One of the possible model applications is integrating with predictive control systems. The principle of such system, based on example of Smith circuit was presented (fig. 12).
The system allows eliminating the influence of delay resulting from measurements performed out of the process space. Such situation takes place, e.g. during visual roughness measurement. The picture registered by camera isn't analysed in cutting zone but away from machine tool. It It causes increasing reaction time while applying traditional control system.

The Smith circuit based control system can improve the measurement correctness.
The proposed model used for control tasks allows executing adaptive and predictive functions at the same time. To achieve this goal it is necessary to modify the Smith circuit by giving the actual parameters of the process (fig. 13). The similar approach is proposed by Ergon [Ergon 2001]. The additional feedback applying enables quick and effective reaction for undesirable changes during cutting. Then the developed optimal control depends not only on model simulations but also on actual process status.

6.3. Rapid prototyping of controllers

The model is made in MATLAB environment. Due to *Real Time Workshop* of MATLAB package one can apply the model to rapid prototyping of industrial controllers. This application is inspired by some papers [Karunakaran & Springi 2004, Takosoglu et al. 2009] considering especially MATLAB/ SIMULINK package [Bucher & Balemi 2006].
Rapid prototyping is design method, relying on optimization of controller structure just before starting of production or making the physical prototype. The verification of assumed solutions goes on by using the virtual, numerical prototype cooperating with process model. The cooperation with a real object is the next step (fig. 14). It requires preparing a real time simulation code, mostly in the *C* language. The essence of rapid prototyping is possibility of quick, automatic processing of model to a virtual prototype (code), which can be tested. It enables detect faults in an early stage of design and preparing the next, improved model of controller. The physical prototype is made only when its virtual equivalent reaches the assumed requirements.

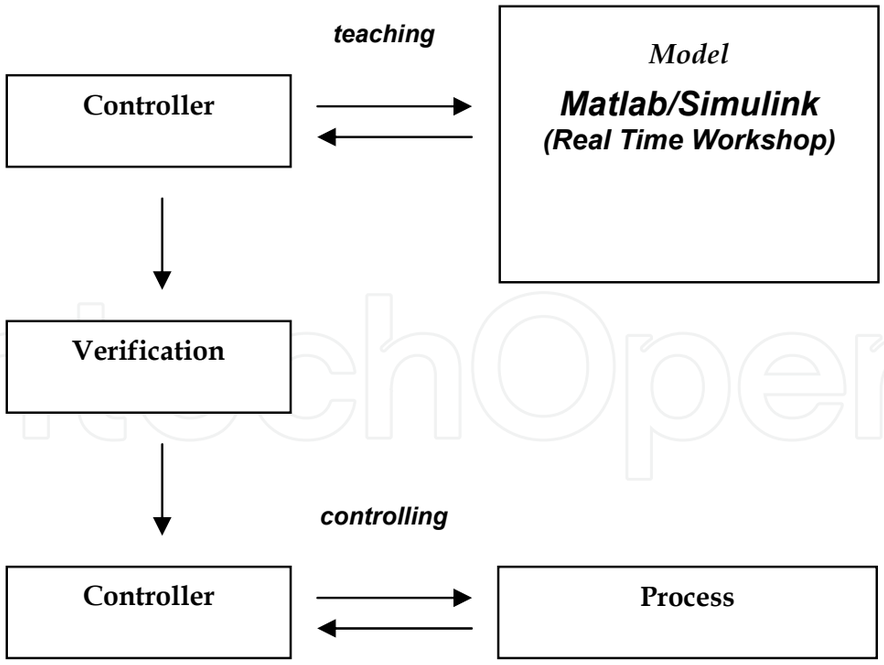


Fig. 14. Application of model for rapid prototyping of controllers

6.4. Integration with CAD/CAM packages

Particularly interesting solution can be application of model in CAD/CAM software (fig. 15). There are many CAD/CAM systems integrated with additional expert or similar modules presented last years in papers [Cemal et al.2005, Chérif et al. 2004, Lin & Kuo 2008, Thomas & Fischer 1996, Yue 2003] but there is no systems using module of dynamical model of cutting process.

Such a module permits evaluation of established cutting parameters and tool geometry from the point of view of cutting process accuracy, efficiency and stability. In the simpliest example the expected amplitude of tool vibration can be predicted, but it is easy to propose additional functions, describing roughness parameters. Working up the criteria and optimal algorithms can enable the automatic selection of cutting parameters and tools for required by constructor quality of machined surface. Putting proposed solutions into effect can cause improving of CAD/CAM packages functionality**.** Thanks to this the considerable shortening of technological process optimization time became possible, what causes significant decreasing of the costs connected with product manufacturing.

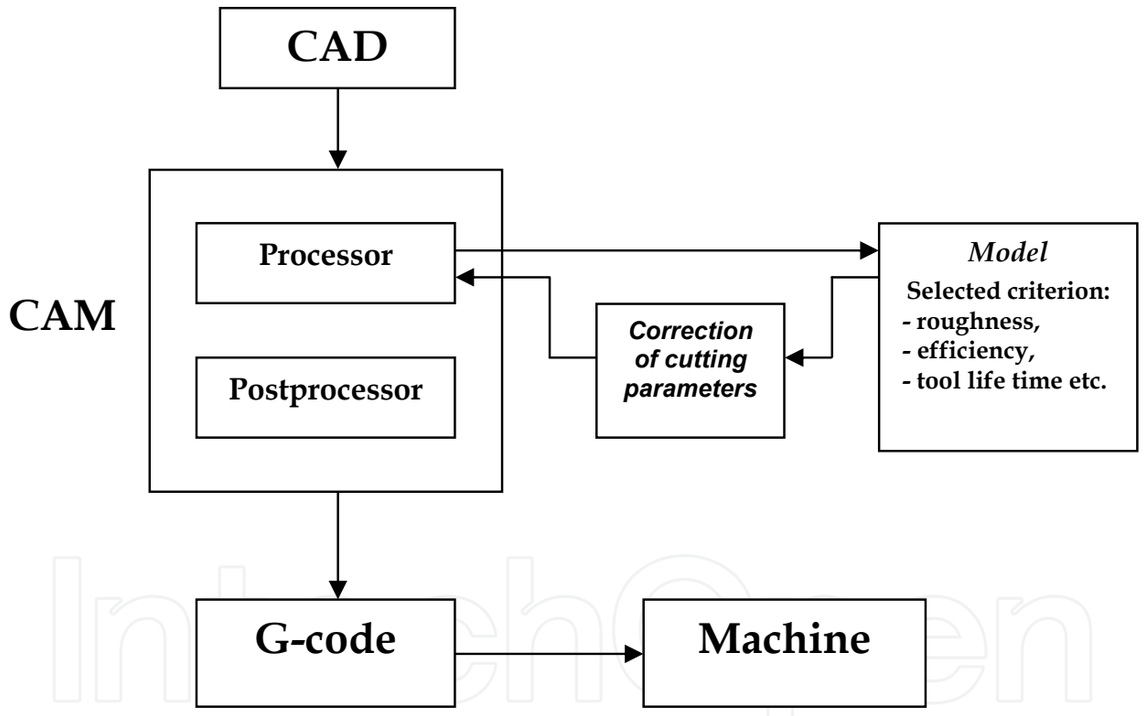


Fig. 15. Application of model as an additional module of CAD/CAM package

7. Conclusions

The proposed model permits to conduct the multi-aspect research in the field of cutting process analysis. It can be also applied for predictive and optimisation tasks, what significantly increases the range of potential applications. Among the others, it enables the analysis of influence on cutting process of such factors, as: cutting parameters, structural and technological features of cutter or cutting system stiffness. Gaining of exact and exhaustive information considering simulated process (tool deflection, cutting force, section

of the cut etc.) also becomes possible. On basis of simulations, many typical, dynamical characteristics can be obtained (time series of selected process factors, phase characteristics, FFT, reconstruction of attractor etc). Due to modular structure of mathematical model the possibility of easy development by considering new factors is also possible.
The quoted features show the possibility of model applying for a large area of issues, such as:

- evaluation of chosen cutting parameters correctness,
- modelling of cutting outline or surface, prediction of roughness,
- dynamical stability process research, particularly in context of modern methods of mathematical analysis,
- rapid prototyping of controllers,
- predictive control systems,
- assistance of technological process design, using extended CAD/CAM packages, etc.

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This book pilots the reader into the future. The first three chapters introduce new materials and material processing methods. Then five chapters present innovative new design directions and solutions. The main section of the book contains ten chapters organized around problems and methods of manufacturing and technology, from cutting process optimisation through maintenance and control to the Digital Factory. The last two chapters deal with information and energy, as the foundations of a prospering economy.

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University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
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