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Machining Process as a Subject of Automatic Control

Evgueni V. Bordatchev*, Peter E. Orban

Integrated Manufacturing Technologies Institute
National Research Council of Canada
800 Collip Circle, London, Ontario, Canada N6G 4X8

ABSTRACT

This report deals with the analysis and the design of a conventional machining system by means of mathematical modeling of the machining process. The paper considers the machining process as a dynamic interaction between the cutting tool and workpiece in space and time that additionally involves the dynamic properties of the machine tool mechanical subsystem, the cutting process, and the cutting motions. An ideal machining system provides an accurately controlled tool path. However, machining experience has shown that the geometric qualities of the machined part are not only defined by the uniformity of the tool path, but are also influenced by the dynamics of the machine tool and cutting process and by the external and internal disturbances. Developed herein, is a systematic approach tying together the four main factors associated with the dynamic processes that play an important role during machining and influence the quality of the machined workpiece. These factors are (a) the kinematic/dynamic disturbances within the cutting/feed motion subsystem, (b) the dynamics of the machine tool mechanical subsystem, (c) the tool-workpiece interaction as a dynamic process, and (d) the forming of the workpiece surface as a dynamic process. The generalized mathematical model of the machining process is developed based on the dynamic relationships between those above-mentioned aspects of the process. The approach performs the dynamic analysis of a machining process for diagnostics, control, and process optimization purposes.

Key words: machining process, dynamics, control, modelling

1. INTRODUCTION

Machining today is an ever-important part of manufacturing. Being competitive in machining and in manufacturing means that parts have to be produced with the required quality, in time, and at cost. The ultimate aim in the planning and executing of machining, as part of manufacturing, is to have a firm handle on all aspects of machining, to be able fully predict, model, simulate, and control the complete process. If all the parameters and metrics of the various processes could be forecasted accurately, based on the characteristics of the actual environment (machines, tools, workpieces), without making a single chip, optimal decisions relating to planning, productivity, quality, cost, and the process could be made.

The machining process has long been fundamentally studied and comprehensive reviews of state-of-the-art and future trends have been reported several times.¹⁻⁶ The following are the main reasons for modelling, simulation, and dynamic analysis of the machining process:

- to recognize the influence of the interaction between the workpiece and the cutting tool on the quality of the workpiece and on the cutting process
- to appreciate the full effect of the machine tool structure on the quality of the workpiece and on the process
- to detect, estimate, predict, and manage the condition of the machine tool and the cutting tool
- to design and/or optimize the machining process
- to develop a control system to realize the highest achievable accuracy and productivity for the existing machine tool and process

Due to the complexity and uncertainty of the machining process, and of its many variants, progress in understanding has been slow, but steady. Researchers have used different approaches to describe the problems based on empirical, analytical, statistical, numerical, and other methods, and their combinations. There is no single best solution; the most

* Correspondence: Email: evgueni.bordatchev@nrc.ca; Telephone: 519 430 7107; Fax: 519 430 7064

adequate method depends on the particular problem addressed. This fact is also reflected in the wide span of the literature.⁶

Based on well-developed fundamentals, this paper deals with the analysis and the design of a machine tool control system by means of mathematical modelling of the machining process. The machining process is considered as a dynamic interaction between the cutting tool and the workpiece in space and time. The presented systematic analysis additionally involves the dynamic properties of the machine tool mechanical subsystem, the cutting process, the process of surface formation, and statistical properties of the cutting and feed motions. It is necessary to note that the cutting process is a significant part of the machining process. Particularly, the cutting process represents the cutting force formation by the relative displacements between the workpiece and the cutting tool. Developed herein, is an overall system approach tying together four main factors associated with the dynamic processes, which play a principal role during machining and significantly influence the quality of the machined workpiece. These factors are (a) the kinematic/dynamic disturbances within the cutting/feed motion subsystem, (b) the dynamics of the machine tool mechanical subsystem, (c) the tool-workpiece interaction as a dynamic process, and (d) the forming of the part surface as a dynamic process. The novel approach presented here performs the dynamic analysis of a machining system for diagnostics, control, and process optimization purposes.

2. THE MACHINING PROCESS - A "BLACK BOX" APPROACH

The general structure of a closed-loop control system can be represented as shown in Figure 1, which consists of:

- a controlled process, whose mathematical model describes a transformation of the controlled variables into output variables
- a controller, represented by a hardware/software system whose mathematical model is a control algorithm transforming the input and feedback variables into controlled variables
- sensors, whose mathematical model represents a transformation of measured variables into feedback variables

Fig. 1. Generalized structure of the closed-loop control system.

In the conventional machining process, the following components represent the elements and variables of the generalized closed-loop control system:

- the controller is the electro-mechanical system represented by the motion control hardware/software
- the controlled process is the machining process, which is the subject of control
- the sensors are some devices, which provide the controller with information about the state of the controlled process and/or values of output variables
- the input variables are the ideal tool path and cutting/feed conditions represented by the CNC
- the controlled variables are the cutting force, cutting speed, depth of cut, cut layer thickness, etc.
- the feedback variables are the actual tool path, cutting/feed motions, tracking errors, machining forces, etc.
- the output variables are the machined surface profile, its parameters and characteristics of macro- and micro-geometry in terms of shape, dimension and surface quality

The machining process is the most important part of any machine tool control system. The correct representation and modelling of the machining process assures the proper design of the control algorithm, and control system functioning. This paper is focused on the systematic representation of the machining process. The machining process is understood as a complex dynamic process of making workpieces that involves the dynamics of the machine tool mechanical structure, the cutting process, the cutting/feed motions, the surface formation, and external/internal disturbances. Based on this understanding, the first approximation of the systematic representation, the "black box" of the machining process, is shown in Figure 2.

Fig. 2. "Black box" of the machining process.

The ideal machining system provides an accurately controlled tool path. However, machining experience has shown that the geometric qualities of a machined part are not only defined by the uniformity of the tool path, but are also influenced by the dynamics of the machine tool and cutting process and by the external and internal disturbances. An existing machine tool as a mechanical system has its own dynamic performance, characterized by its dynamic properties, which are not equal even for machine tools of identical design and static accuracy. Dynamic performance depends on the dynamic characteristics of the mechanical subsystems; e.g. spindle, carriage, etc. and the whole system, on the quality of assembly, and on the geometric quality of the kinematic elements that form the non-uniformities within the cutting and feed motion and essentially affect the final quality of the machined workpiece. During machining, the relative displacement between the workpiece and the cutting tool – for simplicity's sake it will be called tool-workpiece displacement – arises as a response of the machine tool mechanical subsystem on the cutting force as input. These displacements can also be the components of the controlled variables. The mathematical meaning of the machining process is a model of a complex, usually non-linear dynamic transformation of the control variables; for example, the transformation of the cutting force into one of the measured output variables, the surface profile. This model is mainly based on the combination of the dynamic characteristics of the machine tool mechanical structure and the cutting process. In addition, the cutting tool and workpiece geometry and their physical/mechanical properties also play an important role in the machining process and influence the final surface profile; therefore it is necessary to involve them in the mathematical modeling of the machining process.

The problem of the machining process modelling as a relationship between the machine tool and cutting process dynamics and surface profile is quite complicated because the final surface profile is a result of complex tool-workpiece displacements. On the other hand, these displacements are a response of the machine tool mechanical structure on the cutting process, where the pre-machined surface profile and cutting tool geometry is involved.

3. SYSTEMATIC REPRESENTATION OF THE MACHINING SYSTEM

The conventional machining system is a complex electro-mechanical system consisting of:

- the cutting tool subsystem, which provides the tool motion
- the workpiece subsystem, which provides the feed motion

As it is shown in Figure 3, for a lathe machine the workpiece, spindle, and tailstock represent the workpiece subsystem, and the lead screw and carriage assembly represent the cutting tool subsystem. For a milling machine, the spindle and head represent the cutting tool subsystem, and the workpiece, worktable, saddle and knee represent the workpiece subsystem. It is necessary to note from the dynamic point of view that these two subsystems are coupled only in the low-frequency band (up to 50 Hz) during non-machining, because they both are attached to the machine tool bed. The coupling is extended in the frequency range (up to 80 KHz) during actual machining; e.g. when the cutting process exists and forms the tool-workpiece displacements.

The ideal machining system controls the machining tool path accurately. However, machining practice indicates that the geometric qualities of the machined workpiece are not only defined by the predetermined tool path, but are also influenced by the dynamic processes accompanying machine tool operation. Mainly, the following four dynamic processes must be considered.

The first process consists of kinematic (e.g., geometrical errors) and dynamic (e.g., frictional process) disturbances

within the cutting/feed motions and is associated with the structure of machine kinematics. A combination of these disturbances causes non-uniformity of the motions, affects the synchronization between cutting and feed motions, and produces tracking errors. These variations within the feed motion can be as high as 35% with respect to the desired feed rate, even for motion systems with air bearings.⁷

Cutting tool-workpiece interaction plays an important role in the machining process. From the dynamic point of view, the tool-workpiece interaction is understood as a dynamic transformation of the cutting force into tool-workpiece displacements and can be represented by a closed-loop dynamic system.⁸⁻¹⁵ There are two dynamic processes involved in the tool-workpiece interaction. The first is that the cutting force is transformed into tool-workpiece displacements by the dynamics of the machine tool mechanical structure (subsystem). In the other, the tool-workpiece displacements influence the cutting force component through the closed-loop link representation of the cutting process. The tool-workpiece displacements occur always when there is a contact between the cutting tool and workpiece. Sometimes these displacements are converted into a self-excited chatter¹⁶, which causes a poor finished surface profile and excessive wear of the cutting tool. The dynamics of the machine tool mechanical structure is directly involved in the machining process through the formation of tool-workpiece displacements. It means that the machining process can not be modeled and analyzed accurately without the identification of the actual dynamics of the machine tool mechanical structure. In addition, the actual tool path does not conform to the machined workpiece profile due to the space and time variant mechanical-physical-thermodynamic process disturbances in the machining zone¹⁷; therefore, the formation of the workpiece profile must be considered as the ultimate result of the combined effects of all the dynamic processes involved in the cutting tool-workpiece interaction and the mechanical-physical-thermodynamic actions/changes in the processing zone. Based on this, the dynamics of the machine tool mechanical subsystem, the cutting process dynamics, and the formation of the workpiece profile are respectively the second, the third and the fourth dynamic processes that influence the machined surface quality.

Fig. 3. Cutting tool and workpiece subsystems for lathe and milling machines.

Figure 4 illustrates the systematic representation of a complex machining system involving the dynamics of:

- the machine tool mechanical subsystem
- the cutting process
- the cutting and feed motions
- the surface profile formation

The main difference of the suggested systematic representation is in the analysis of the machining process with respect to the quality of the machined surface profile. The purpose is to produce a workpiece with the prescribed geometric quality and maximum productivity or minimum machining cost. The geometric quality of the machined workpiece is described in terms of shapes, dimensions, surface parameters, and characteristics. All of these parameters can be calculated directly from the shape representation and surface texture as a geometric function; e.g., profile amplitude versus position. The formation of the shape and surface profile is considered a dynamic process, which is a transformation of the tool edge motions into the shape and surface texture, additionally including the tool edge geometry and the mechanical-physical-thermodynamic disturbances. These disturbances represent the independent processes in the cutting zone, such as an elastic/plastic deformation of the workpiece, etc.

The cutting tool edge motion is a combination of the actual cutting/feed motions and the relative tool-workpiece

displacements. The complexity arises because these motions and displacements are dynamically coupled, but have different frequency bandwidths of their random components. The frequency bandwidth of feed motion variations is up to 300 Hz and tool-workpiece displacements are up to 40 KHz. There are also different sources of the random component formation. The variations within the cutting/feed motions are formed mostly by kinematic (e.g., geometric errors of the kinematic elements) and dynamic (e.g., the friction process within the kinematic joints) disturbances. The tool-workpiece displacements are the result of tool-workpiece dynamic interactions where the closed-loop system of the machine tool mechanical subsystem and cutting process is involved. Cutting force arises only if there is material being removed from the workpiece. If there are no tool-workpiece displacements (which means no cutting process), only the actual cutting/feed motions determine the tool edge motions. This is the basis of how to recognize the main dynamic signatures of cutting/feed motion non-uniformity within tool edge motions. The tool-workpiece displacements generate the cutting force through the cutting process. In turn, the cutting force generates the tool-workpiece displacements through the machine tool mechanical subsystem, which in this context can be called the "machine tool transfer subsystem". The relative tool-workpiece displacements in combination with the tool edge geometry represent an instantaneous undeformed chip thickness. Experiments¹⁷ have shown that the cutting force has the independent random component, called the cutting force noise, which is not dynamically coupled with the tool-workpiece displacements. The sources of the cutting force noise are the chip formation and friction processes between the cutting tool, chip, and workpiece. This is the basis for the understanding, modelling, and systematic analysis of the machining process as a subject of automatic control.

Fig. 4. Systematic representation of a machining system.

4. GENERALIZED DYNAMIC MODELLING OF THE MACHINING PROCESS

In general, the machining process can be modelled by the following equation:

$$\begin{cases} \frac{dx(t)}{dt} = \Phi(x(t), u(t), f(t), f^*(t)) \\ z(t) = \Psi(x(t), u(t), f(t)) \end{cases} \quad (1)$$

Where $\mathbf{x}(t)$ is the vector of machine-tool responses related to the relative workpiece-tool displacements and is defined in terms of the standard machine-tool coordinate system (X, Y, Z). The components of vector $\mathbf{x}(t)$ are the tool edge motions; displacements of the spindle, carriage, and workpiece; signals from different sensors, vibro-acoustic emissions, and temperature effects, etc.

$\mathbf{u}(t)$ is the control vector having different machining variables as its components, such as the prescribed tool path, spindle velocity, feed rate, depth of cut, etc.

$\mathbf{f}(t)$ is the applied cutting force vector, which is defined in terms of a constant (mean value) and a time-varying component, and it is a measure of the actual cutting force.

$\mathbf{v}(t)$ is the state vector of the actual cutting process and consists of the tool wear parameter, tool interface breakage parameter, etc. as its components.

$\mathbf{f}^*(t)$ is the cutting force noise vector. The components of $\mathbf{f}^*(t)$ correspond to the independent dynamic processes taking place within the processing zone.

$\mathbf{z}(t)$ is the product quality vector and its components define the acceptable parameters of the final product in terms of surface profile, dimensional accuracy, surface finish, etc.

$\Phi(\cdot)$ and $\Psi(\cdot)$ are operators of the indicated variables. The problem of mathematical modelling of the machining process is in finding the definition of these operators, which are non-linear in general, and represent the dynamics of the machine tool mechanical subsystem, the cutting process, and surface profile formation.

With the generalized dynamic model in equation (1), the tasks of control and diagnostics are formulated as follows:

- the task of control consists of the determination of the control vector $\mathbf{u}(t) = (u_1, u_2, \dots, u_m) \in \mathbf{U}$ such that it provides the prescribed product quality $\mathbf{z}(t) = (z_1, z_2, \dots, z_n) \in \mathbf{Z}$ with the appropriate cutting process state $\mathbf{v}(t) = (v_1, v_2, \dots, v_k) \in \mathbf{V}$, within the sets $\mathbf{U}$, $\mathbf{Z}$, $\mathbf{V}$ of permissible parameters for each corresponding $\mathbf{u}(t)$, $\mathbf{z}(t)$, and $\mathbf{v}(t)$ vectors
- the task of diagnostics consists of finding operators $L_z(\cdot)$ and $L_v(\cdot)$, which describe the monitoring of product quality $\mathbf{z}(t)$ and the cutting process state $\mathbf{v}(t)$ by measuring the machine-tool responses $\mathbf{x}(t)$ for appropriate diagnostic actions such that

$$\begin{aligned} \mathbf{z}(t) &= L_z(\mathbf{x}(t)) \\ \mathbf{v}(t) &= L_v(\mathbf{x}(t)) \end{aligned} \quad (2)$$

Figure 5 shows a generalized dynamic model of a machining process based on a lathe machine. The machine has three principal components "A", "B", and "C"; these represent the spindle, carriage, and the tailstock, respectively. The dynamics of these elements are responsible for the dynamic behaviour of the lathe structure, and play an important role in the formation of final surface profile. The tool-workpiece contact point changes during machining, and so do the dynamics of the machining process. The workpiece geometry is involved in the machining dynamics, which is also different for various workpieces. Hence the analysis of the machining process is a time-space-varying system.

Based on the systematic representation and previous discussions above, and making use of the differential operator $p = d/dt$, equation (1) can be expressed by the following system:

$$\begin{cases} \mathbf{x}(t) - \mathbf{W}(p)\mathbf{f}(t) = 0 \\ \mathbf{f}(t) = \mathbf{f}^*(t) - \mathbf{G}(p)\mathbf{x}(t) \\ \mathbf{r}(t) = \mathbf{Q}(p)(\mathbf{x}(t) + \mathbf{u}(t) + \mathbf{u}^*(t)) \\ \mathbf{z}(t) = \Sigma(\mathbf{r}(t)) \end{cases} \quad (3)$$

where $\mathbf{W}(p)$ is the 3×3 differential matrix operator of the machine-tool mechanical subsystem, which transforms the cutting force vector $\mathbf{f}(t)$ into the vector of workpiece-tool tip related displacements $\mathbf{x}(t)$;

$G(p)$ is the 3×3 differential matrix operator of the cutting process and transforms the $\mathbf{x}(t)$ vector into additional components of the $\mathbf{f}(t)$ vector;

$\mathbf{f}^*(t)$ is the force noise vector of the cutting process, and represents the non-linear properties of the cutting process;

$Q(p)$ is the 3×1 differential matrix operator, which represents the surface profile formation as a dynamic process;

$\mathbf{r}(t)$ is the radius vector of the machined surface profile, and results from applying $Q(p)$ to $\mathbf{x}(t)$;

$\mathbf{z}(t)$ is the product quality vector, its components are ovality, cylindricity, arithmetic average, root mean square, etc., and is finally formed from the workpiece surface profile, represented by $\mathbf{r}(t)$, and by some statistical operator Σ .

Fig. 5. Generalized dynamic model of a machining process as a subject of automatic control.

Figure 6 illustrates the block diagram of the machining process, represented by equation (2). Note the following:

- The closed-loop link is negative in nature. The dynamic tool-workpiece interaction is such that an increasing cutting force provides increasing relative tool-workpiece displacement, and that in turn decreases the cut layer thickness and cutting force. As the tool-workpiece displacement decreases, it causes an increase of the cut layer thickness and cutting force. This cycle is repeated during the cutting and can be understood as a self-organized dynamic process.
- The cutting tool-workpiece interaction forms a non-linear dynamic link between the tool and the machined workpiece. As a first approximation, this non-linear link can be described as a combination of two components. The first component is the operator $G(p)$, which represents the dynamic characteristic of the cutting process. This operator mathematically expresses the transformation of the relative tool-workpiece displacements into the

corresponding $\mathbf{f}^{**}(t)$ part of the cutting force $\mathbf{f}(t)$. The second component corresponds to the random (in space and time) cutting process noise $\mathbf{f}^{**}(t)$, which symbolizes the non-linear properties of the dynamic process taking place within the processing zone; e.g., chip formation processes and friction processes between cutting tool faces, chip and workpiece.

- The dynamics of the machine tool mechanical structure is represented by the differential matrix operator $\mathbf{W}(p)$, which combines the dynamic properties of the workpiece and cutting tool subsystems. The following sequence for the modelling and identification of operator $\mathbf{W}(p)$ is suggested:
 - ♦ Model each of the dynamically principal points, e.g., “A”, “B”, and “C”, as a mass-spring-damper system, which is non-orthogonal in space as shown in Figure 5. The dynamic parameters of this model are identified by applying the algorithm developed earlier.¹⁸
 - ♦ Based on the geometry and the dynamics of the workpiece, decide how to analyze the part, – as a rigid body or as a system with distributed parameters.
 - ♦ Apply the finite element method to calculate $\mathbf{W}(p, \ell)$ for a system with a moving load in the point of contact between the cutting tool and workpiece, where ℓ is the contact point coordinate along the Z-axis.

Fig. 6. Block diagram of the machining process dynamics.

- The tool path (NC program) defines the quasi-static equilibrium state of the tool edge motions. The deviations within the motions are defined by the non-uniformities of the cutting/feed motions and the relative tool-workpiece displacements.
- The formation of the machined surface profile is described as a dynamic process, the transformation of the tool edge motions into the surface profile. This transformation results in the complicated space-time-varying motions, which produce the surface profile as shown in Figure 7. In time linear approximation it can be described mathematically as follows:

$$\mathbf{r}(t) = \mathbf{Q}(p)\mathbf{x}(t) + \mathbf{r}^*(t) = Q_{x_1,r}(p)x_1(t) + Q_{x_2,r}(p)x_2(t) + Q_{x_3,r}(p)x_3(t) + \mathbf{r}^*(t) \quad (4)$$

where $\mathbf{r}^*(t)$ is the noise of surface profile formation due to existing independent physical processes; e.g., elastic/plastic deformations, tool-chip-workpiece friction, etc. within the processing zone that provide the difference between the actual tool edge motions and final surface profile.

Thus, designing a control system for the machining process involves the following:

- (a) modelling and identification of the dynamics of the machine-tool mechanical subsystem with given workpiece geometry
- (b) modelling and identification of the cutting process dynamics
- (c) modelling and statistical estimation of the cutting force noise

- (d) modelling and statistical estimation of the cutting/feed motions non-uniformities, which represent the machine-tool technical performance
- (e) modelling and identification of the dynamics of surface profile formation

Fig. 7. Formation of surface profile as a dynamic process.

5. CONCLUSIONS

A new systematic approach for the dynamic modelling of the machining process as a subject of automatic control has been presented. The principal advantage of the proposed method is the modelling and analysis of the machining process, established from the point of view of the primary mission of a machine tool: production of a workpiece with given quality. The concept is based on the analysis of cutting tool-workpiece interaction as a dynamic process involving the dynamics of the machine tool mechanical subsystem, workpiece geometry, dynamics of the cutting process, non-uniformities of cutting/feed motions, and the dynamics of surface profile formation. The key points of this concept are: (a) involving the dynamics of the cutting processes in the machining process dynamics, and (b) not modelling and analyzing the cutting process dynamics separately from the machine tool mechanical subsystem dynamics and workpiece geometry.

The presented results open new directions for the analysis of machine tool functioning towards virtual machining with the involvement of actual dynamic characteristics and technical performance of an existing machine tool. The suggested dynamics of the machining process also defines the dynamic quality of the machine tool and allows for estimating the limits of accuracy, the machinability of a workpiece with required geometrical quality, and for designing a machine tool with desired dynamic characteristics and performance.

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