A NOVEL CONTROL SYSTEM FOR CHATTER SUPPRESSION IN TURNING

Gabriel Frumuşanu, Ionuţ Constantin, Alexandru Epureanu

"Dunărea de Jos" University of Galaţi, Romania,
Department of Manufacturing, Robotics and Welding Engineering
gabriel.frumusanu@ugal.ro

ABSTRACT

The increasing requirements concerning machining precision and efficiency call for the development of machining system new control strategies, which should enable the process performance maximization. By assuming the productivity as main performance criterion, in this paper a novel control system based on a dedicated strategy for machining process control is presented at conceptual level. The process control strategy lays on a permanent assessment of the process current dynamical state, by referring the system operating point position to the stability limit, and on a periodic (but frequent) cutting regime adjustment in order to keep this point in the stability domain, as close as possible to the stability limit. The system operating point position is assessed by cutting-force on-line monitoring, followed by a dedicated feature extraction and reference to an interval of values characterizing the stability limit proximity domain. The system control algorithm has a sequential character, and consists in step by step increasing / decreasing the cutting speed or the feed rate, depending on the feature value position respect the target interval.

KEYWORDS: chatter suppression, cutting force signal featuring, online monitoring, stability limit proximity, turning

1. Introduction

Chatter, more or less obvious, inherently affects the cutting process. Chatter occurrence may lead to negative effects concerning surface quality, cutting tool life, and machining precision. The chatter does not mean every time instability, but it is frequently a source to initiate the regular regime of periodic vibrations, which is unacceptable, because it might totally compromise the machining system performance or it might affect its integrity.

Diverse solutions for suppression of the chatter which does appear during the machining process have already been suggested in the dedicated literature. For example, a feed forward multi-layered neural network was developed to predict the roughness of the surface generated on a CNC lathe, based on three cutting regime parameters (cutting depth, cutting speed and feed rate); then, a control algorithm was imagined and implemented into a control system, which finds the cutting regime parameters to be used for obtaining the imposed roughness of the worked piece surface [4]. Similarly, an in-process roughness adaptive control system in turning, based on artificial neural networks and including two subsystems, was conceived [7]; the first subsystem predict surface roughness, while the second adapt the feed rate, using data from not only the cutting parameters, but also vibration signals, detected by an accelerometer sensor. Another in-process surface roughness adaptive control system, for the same kind of machining operation, using fuzzy-nets modeling and tool vibration measured with an accelerometer, was proposed [5]. The goal of this system is to predict the turned surface roughness, to compare it with the desired specifications, and to adapt the feed rate in order to obtain a surface roughness no higher than it is necessary. An in-process surface roughness estimation procedure, based on least-squares support vector machines, is also proposed [6]; the cutting conditions, parameters of tool geometry, and features extracted from the vibration signals constitute the input information to the system. A combination of neural networks, fuzzy logic and PSO evolutionary strategy methods was used in modeling and adaptively controlling the ball-end milling process [8]. A combined system for off-line optimization and adaptive adjustment of cutting parameters was built based on hybrid process modeling, off-line optimization and feed-forward neural control scheme.

A technique for active control of the machining process performed for suppressing the tool vibration and leading to improved surface texture, dimensional accuracy and enhanced productivity was suggested [1]. It consists in an active tool holder, capable of isolating the cutting tool from the vibration of the machine-tool structure, by mean of a Kalman estimator-based control strategy, a high bandwidth magnetostrictive actuator, and two accelerometers. On the same direction, the use in centerless grinding of an active vibration control system, based on a reduced updated FE machine model, was simulated [2].

After analyzing the existing solutions, we may notice some of their drawbacks:

- In most of the cases, the control system action is focused directly on the generated surface roughness, without considering the aspects concerning the machining system stability, which is essential;

- The perturbations which always appear during the cutting process, can significantly affect the roughness prediction effectiveness and for this reason the control system might take inappropriate decisions;

- The implementation of solutions for eliminating the vibration negative effects, on the base of an active control system, is difficult for the existing types of machine tools, because it requires a dedicated design of certain subsystems or component parts and the existence of appropriate dynamical models.

In this paper we present a new strategy to be used for chatter suppression during the machining process. A novel control system, working on this base, with application in turning, was also developed, at conceptual level.

2. Chatter suppression strategy

Generally speaking, the cutting regime of a machining process is characterized by the cutting speed, the cutting depth, t, and the feed rate, s. If we now consider a tri-orthogonal reference system, having as axis the cutting speed, v, the chip thickness, a, and the chip width, b (off course, between s and t, on one hand respectively a and b, on the other hand, existing a direct connection), then a determined point corresponds, in this space, to the cutting regime (Fig. 1). We will further refer to this point as "the system operating point".

In given conditions concerning a certain machining process, taking place on a specified machining system, the system operating point co-ordinates take values from a well defined closed domain, whose limits are imposed by technical reasons. Also generally speaking, inside this domain we may find two sub-domains: the stability domain and the instability domain. The stability domain is the locus of the system operating points corresponding to a stable process (meaning chatter absence), while the instability domain is formed by operating points where the process is affected by chatter. The delimitation between the stability domain and the instability domain is made by the stability limit. In the case of a turning process, the stability limit looks like the surface 123456 (Fig. 1).
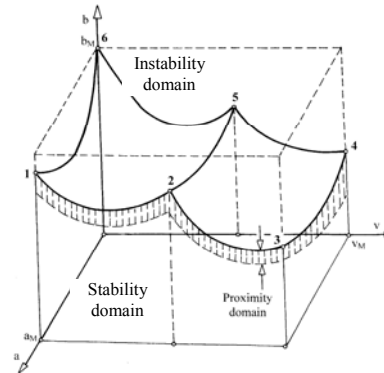

Fig. 1. *3-D stability chart*

The main inconvenient of the existing strategy to avoid chatter occurrence issues from disregarding the fact that the stability limit of a certain cutting process depends on its own parameters but also on the local characteristics of the machining system (dynamical stiffness, natural frequencies etc.), last ones permanently modifying during the manufacturing process. It follows that the stability domain dimensions and position are also permanently changing during machining, referred to the instability domain. In other words, although a certain stability chart is characteristic only for an instance (or, let say for a very small domain of the tool path) it is considered unchanged for the entire process.

If the current approach concerning the cutting process stability is accepted, then the cutting regime does not follow the stability domain evolution. Thus, after a machining process is set, according to the initially known conditions, the cutting regime is kept constant, at a low enough level to avoid instability, which is obviously meaning a loss of productivity.

In Fig. 1, a narrow zone, corresponding to what we will further call "proximity domain" can be observed in the stability limit nearness. Here, the system behavior is stable, but early sights of instability can be revealed.

In the case of a given machining system, the stability can be reached by keeping its operating point inside the stability domain. We may accept that the cutting speed and the chip width are the suitable variables for dynamical stability control and the target for a control system should be to bring and to permanently maintain the system operating point in the proximity domain.

In [3], a novel method for early detection of the regenerative instability is proposed. The method involves the following actions:

- Online recording the cutting force signal as time series.
- Assessment of the process current dynamical state by using dedicated features, extracted by processing the cutting force signal.

- Modelling and prediction of the process dynamical state evolution, by following a specific algorithm.

Hence we found that by online monitoring the variation of a chosen cutting force signal feature, we could learn when the system operating point reaches the proximity domain. Because it gives indications about the system operating point position relative to the stability limit, we will further call such a cutting force signal feature "indicator", denoted by I.

If we choose, for example, the cutting speed as manipulated variable in order to adjust the system operating point position relative to the stability limit and we represent the indicator variation depending on the cutting speed magnitude, it appears like the curve depicted in Fig. 2.
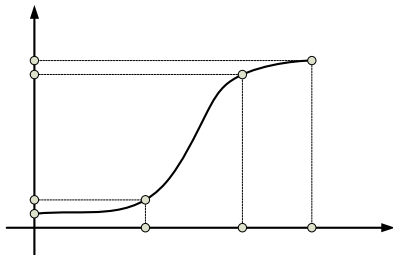

Fig. 2. *The dependence between the indicator I and the cutting speed, v*

The section AB of the curve corresponds to a completely stable process, while CD section – to a process affected by chatter. The intermediary section BC, characterized by I values between I_m and I_M shows the passage of the system operating point through the proximity domain.

In conclusion, our chatter suppression strategy is to control the cutting speed on such a manner as the values of the indicator I remain always in the interval $[I_m, I_M]$. This way, the process remains, at limit, stable, while its productivity is maximized.

3. The concept of the novel control system

The structure of the novel control system, working on the base of the chatter suppression strategy from above is presented in Fig. 3.

The signal proportional to the cutting force is generated by strain gauges, placed on the cutter or on the tool holder and then, communicated to a data acquisition system. The data accounting frequency should be high enough to ensure a sufficient number of cutting force successive values for every cutting cycle (worked piece rotation), in order to enable a rigorous calculation of current value of the indicator I.

The chatter control system assesses the current value of the indicator, compares it with the limit values, I_m and I_M and takes the decision concerning the opportunity of cutting regime adjustment and the magnitude of the adjustment, which is effectively realized by applying a coefficient K_a to the initial

value of one among the cutting regime parameters (rotation speed n_p, feed rate s_p). If the current position of the system operating point is below the proximity domain, K_a is greater than 1, while if it is too close to the stability limit, K_a is smaller than 1.
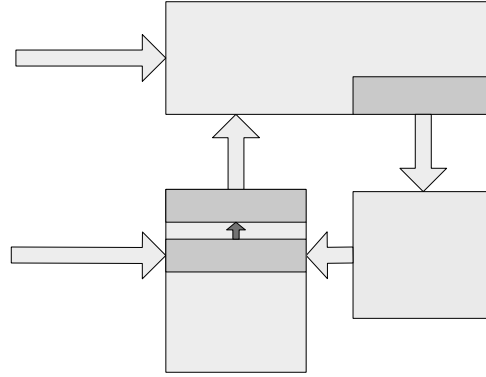

Fig. 3. *The structure of the control system*

As regards the indicator, [3] gives more alternatives for the cutting force signal feature to be used; among them, the ratio between the maximum and the mean amplitude of signal DFT, in a given frequency domain seems the most suitable.
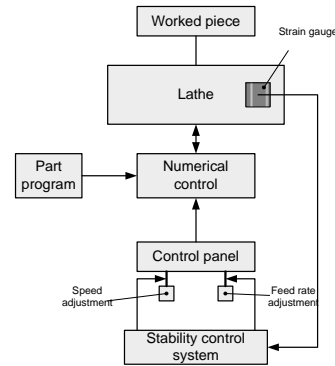

Fig. 4. *The interconnection between the lathe and the control system*

The intervention onto the lathe technological settings can be realized by using the facilities "*cutting speed override*" and "*feed rate override*" provided by the machine tool NC. They allow piece rotation speed and tool feed rate continuous modification between minimum and maximum limits, relative to their initial set values. The interconnection between the lathe and the control system is shown in Fig. 4.

The K_a coefficient value is always reassessed for the current cutting cycle, by applying to its last value a multiplier, λ_k,

$$K_a = K_a \cdot \lambda_k . \qquad (1)$$

The values for λ_k are chosen depending on the indicator values for the current and for the previous cutting cycle (I_k, respective I_{k-1}), according to the algorithm presented in Table 1.

Table 1. *λ coefficient settings*

I_{k-1}	I_k	λ_k
$< I_m$	$< I_m$	λ_1
$\in [I_m, I_M]$	$< I_m$	λ_2
$> I_M$	$< I_m$	λ_2
Irrelevant	$\in [I_m, I_M]$	1
$> I_M$	$> I_M$	λ_3
$\in [I_m, I_M]$	$> I_M$	λ_4
$< I_m$	$> I_M$	λ_4

The relations between the five possible values of the λ_k multiplier are the following:

$$\lambda_4 < \lambda_3 < 1 \text{ and } \lambda_2 > \lambda_1 > 1 . \qquad (2)$$

The particular magnitude for each multiplier value must be established initially starting from the experience in applying the control system in similar previous machining processes and then adjusted according to the current process peculiarities.

4. Conclusion

In this paper, a novel control system for chatter suppression in turning is presented at conceptual level. The process control strategy lays on a permanent assessment of the process current dynamical state, by referring the system operating point position to the stability limit, and on a periodic (but frequent) cutting regime adjustment in order to keep this point in the stability domain, as close as possible to the stability limit. The system operating point position is assessed by cutting-force on-line monitoring, followed by a dedicated feature extraction and reference to an interval of values characterizing the stability limit proximity domain. The system control algorithm has a sequential character, and consists in step by step increasing / decreasing the cutting speed or the feed rate, depending on the feature value position respect the target interval.

Although a significant productivity increase is expected because of cutting regime intensity maximization in chatter-free conditions, the novel control system efficiency can be evaluated only after its practical implementation on a real machine tool.

We also must notice that the novel control system implementation firstly requires adapting the classical machine tool NC system in order to allow the cutting regime adjustment after every single cutting cycle, which is possible.

REFERENCES

[1] El-Sinawia, A.H., Kashanib, R., *Improving surface roughness in turning using optimal control of tool's radial position*, J Mater Process Tech 167, 2005, pag. 54–61.
[2] Fernandes, M.H. et al., *Simulation of an active vibration control system in a centerless grinding machine using a reduced updated FE model*, Int J Mach Tool Manuf 49, 2009, pag. 239–245.
[3] Frumusanu, G.R., Epureanu, A., Constantin, I.C., *Method for early detection of the regenerative instability in turning*, Int J Adv Manuf Technol, DOI 10.1007/s00170-011-3383-6, 2011.
[4] Karayel, D., *Prediction and control of surface roughness in CNC lathe using artificial neural network*, J mater process tech 209, 2009, pag. 3125–3137.
[5] Kirby, E.D., Chen, J.C., *Development of a fuzzy-nets-based surface roughness prediction system in turning operations*, Computers & Industrial Engineering 53, 2007, pag. 30–42.
[6] Salgado, D.R., Alonso, F.J., Cambero, I., Marcelo, A., *In-process surface roughness prediction system using cutting vibrations in turning*, Int J Adv Manuf Technol 43, 2009, p. 40–51.
[7] Zhang, J.Z., Chen, J.C., Kirby, E.D., *The development of an in-process surface roughness adaptive control system in turning operations*, J Intell Manuf 18, 2007, pag. 301–311.
[8] Zuperl, U., Cus, F., Reibenschuh, M., *Modeling and adaptive force control of milling by using artificial techniques*, J Intell Manuf, DOI 10.1007/s10845-010-0487-z, 2010.

Un nou sistem pentru eliminarea vibrațiilor din timpul strunjirii

—Rezumat—

În lucrarea de față este prezentat, la nivel conceptual, un nou tip de sistem de control, având ca scop eliminarea vibrațiilor și maximizarea productivității procesului de strunjire. Strategia de control al prelucrării se bazează pe evaluarea permanentă a stării dinamicii curente a procesului, prin determinarea poziției punctului de funcționare relativ la limita de stabilitate și pe ajustarea periodică a intensității regimului de așchiere, pentru menținerea acestui punct în domeniul stabil, cât mai aproape de limita de stabilitate. Poziția punctului de funcționare se găsește prin monitorizarea on-line a forței de așchiere, urmată de calculul unui indicator specific al semnalului și referirea acestuia la un interval de valori care caracterizează proximitatea limitei de stabilitate.