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Method for Online Control of the Cutting Process Stability

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ABSTRACT

The paper refers to a method for online control of dynamic stability in cutting processes, stability characterized by the absence of relative self excited vibration between tool and part, and also to the necessary equipment for the implementation of this method on machine tools for mass production of batches of different products. . The method has the following advantages:

i) ensuring the permanent use, in optimal terms of dynamic stability, of the machining system processing capacity;

ii) it can be applied to all machining systems based on cutting, where the dynamic instability exhibits self-excited vibration between tool and part;

iii) in the designing stage, the method allows satisfying both the specific dedicated machining systems requirements and the specific universal flexible or dedicated machining systems;

iv) when put in use, it requires a smaller number of settings, to grant changes in terms of machining system structure or operation

The necessary equipment for implementing this method can be designed as an independent unit that can be attached to the machining system, in which case its construction should make it rather common, but also as a dedicated and integrated CNC machining system unit. The paper presents a study of the method application for turning operation.

KEYWORDS: chatter, stability, online control, machining system dynamics, cutting process

1. Introduction

Stability is one of the key factors limiting the intensity of the cutting processes. Lack of process stability can be translated into the occurrence of unwanted vibrations of high amplitude between the part and the cutting tool. Instability leads to appearance of inadequate quality surfaces and, at the same time causes premature tool and machine tool wear.

In order to avoid chatter, one must increase the stiffness of the machine tools in the design phase, but this method involves supplementary investment. In addition, the effectiveness of this method is not valid for all processes.

Usually, the dynamic stability control is applied to the cutting control methods based on offline identification. Modeling the stability of the machining systems is a particular problem since many factors are affecting stability. Models encountered in literature are generally based on some simplifying assumptions that limit their accuracy.

Those models often require knowledge of additional information on the tool or part difficult to assess in practice. For example, in [5], the authors construct a model for the turning process using boring bars with diamond round nosed tools in order to predict the appearance of chatter.

BUDAK [2] - [4] have developed a multidimensional model of stability for the turning process, model that takes into account three-dimensional movement of the cutting tool.

In the online control of dynamic cutting stability domain, a recently published method is based on the use of a sensor, to identify the occurrence of self-excited relative vibration between tool and part, followed by cyclical changes in cutting speed, with appropriate frequency and amplitude, until chatter disappears. Suleiman [1] proposed a system which does not identify the system lobe stability by the analytical approach, but selecting the optimal speed by increasing the spindle speed until chatter appears. One of the disadvantages of these methods is that the dynamic stability control system reacts only after the limit of stability has been reached and, consequently, after self-excited vibrations have already appeared, and thus providing no preventive reaction to online avoid the instability.

Another disadvantage is that when the operation point is inside the stability domain of the cutting process, the dynamic stability control system will not control the cutting process; despite the fact that the operation point could be placed near the stability limit and thus the productivity could be increased, sometimes significantly. As along the cutting tool trajectory, both dynamic stability limit, and the position of operation point within the area of dynamic stability vary widely, there is almost always an unused reserve for increasing productivity.

2. Problem Formulation

The technical problem considered in this paper is to provide a method of online dynamic stability control of cutting processes. By this method during the cutting process, for the most of the capacity of the machining system can be used, while maintaining the process stability, even when part dimensions and material characteristics and/or machining system characteristics vary in time and space.

3. Problem Solution

In order to control the position of the current machining system in relation to the dynamic stability limit, the online control method proposed in this paper consists in monitoring simultaneously a pair of signals obtained from two sensors. One of the signals whose variation in time can be considered to be proportional to the time variation of the cutting force will be called force-signal. The second signal, which can be considered proportional to the acceleration of the relative motion between the tool and the part, will be called acceleration-signal.

These signals are recorded as a pair of time series and are transmitted to an embedded system which has the role of stability control. Force and acceleration signals are processed by the stability control system as an algorithm consisting of the following steps:

Step I - elimination of slow time-varying component, separately for each pair of signals;

Step II - scaling of the two filtered signals;

Step III - Fourier transform of the two signals;

Step IV - establishing the operation point position relative to the dynamic stability limit;

Step V - establishing the parameters of the cutting process or machining system characteristics that will act as control variables, and modify them to the values programmed in order to achieve a previously set goal.

Step IV is based on the analysis of Fourier transforming the two signals, and based on the observation that in cases where the cutting process is in the area of instability, natural frequencies of the machining system are distinguished with clarity, both in force and acceleration signals, while in cases where the process of cutting is in the area of stability, the two signals differently highlight the machining system frequencies.

Thus, the force signal shows no dominant frequencies in the stability domain, while the acceleration signal divides the stability domain into two parts, a first domain, which will be called the sensitive stability domain and another, which we name the insensitive stability domain. The sensitive stability domain is near the limit of stability and is characterized by the fact that the natural frequencies of the machining system are evidenced better in the acceleration signal when the process is closer to this limit.

Insensitive stability zone is formed by the remaining domain of stability. This domain is characterized by the fact that both signals, natural frequency of machining system does not distinguish. In conclusion, after the analysis in Fourier transforms of the two signals regarding the domain where the cutting process is current, we may consider that:

i)-if both signals show a natural frequency of the machining system, then the process is in the instability domain;

ii)-if the force signal does not indicate any natural frequency, while the acceleration signal does, then the process is in the sensitive stability domain, closer to the stability limit where the acceleration amplitude signal for the corresponding natural frequency of the system is bigger;

iii)-if neither of those signals indicates its frequency, then the process is in the insensitive stability domain.

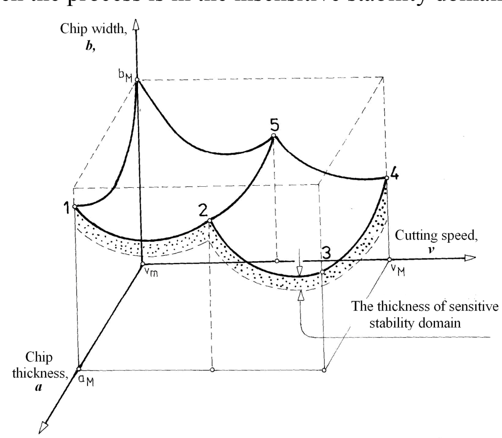

Fig.1. *Stability limit position*

Figure 1 presents the stability limit position, represented by *1-2-3-4-5* surface, in possible values space of cutting and process parameters namely, the cutting speed between the minimum value v_m and the maximum value v_M; the chip thickness between zero and the maximum value a_M, the chips width, between zero and the maximum value b_M. Above the stability limit is the instability domain. Below this limit is the stability domain, which is composed of the sensitive stability domain, located in the surface vicinity *1-2-3-4-5*, and whose thickness is marked in the figure, and the insensitive stability domain is composed of the remaining domain of stability.

4. A Case Study

In this case study, the online control method of the dynamic stability described in the first part of this paper is applied to the turning process. As shown in Figure 2, as a signal whose time variation is considered proportional to the time variation of the cutting force, and that, therefore, is monitored as the force signal, is obtained from a force transducer, which is mounted in the tool support. In addition, a signal that can be considered proportional to the acceleration of the relative motion between the tool and the part, and therefore, it is monitored as the acceleration signal obtained from an accelerometer.

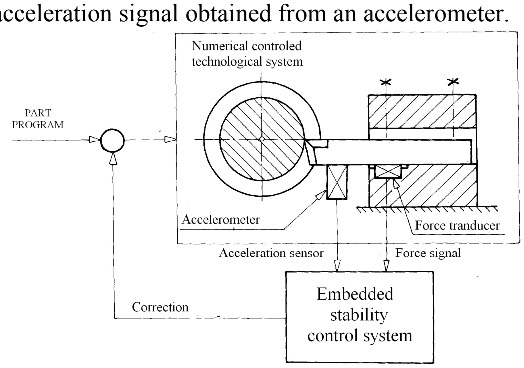

Fig. 2. *The equipment used for the stability control*

Both signals, first provided by a force transducer fixed on the cutting tool, and the second signal, provided by an acceleration transducer also fixed on the cutting tool, are numerically acquired, with a frequency high enough to be able to capture variations over time with frequencies close to the machining system natural frequencies. For example, common universal lathes have two major common frequencies, the first, about 150 Hz, and the second ranging between 1000 and 2500 Hz. As a result, an acquisition frequency of 20 kHz or more is required.

Equipment for the online control of the cutting stability serves to the method described above and consists of:

a) sensors that generate force signal and acceleration signal, according to the method;

b) electronic elements necessary for the acquisition of two signals that are integrated in an embedded computing and control system, which, in turn, by processing these signals according to the algorithm described in the first part of this paper, determine the necessary changes for the current operation point for the machining system in relation to the stability limit, in order to achieve a previously established goal, such as productivity enhancing while avoiding chatter problems;

c) two communication interfaces, a communication control unit which ensures modifications for the control variables, so that this goal be achieved, and another, to communicate with the operator, that assures permanent display of the current point of operation, but also allows the operator to set range for the natural frequency of the machining system and the limit values of amplitudes A_f and A_a for the force and acceleration signals, in order to discriminate the position of the current operating point position in sensitive or insensitive stability domain or if the current operation point is in the instability domain.

5. Applying the Method

These signals are recorded as a pair of time series and then sent to the embedded stability control system, which are being processed. Figure 3 shows two signals acquired simultaneously, as pair signals, resulting from the application of laboratory experimental method.

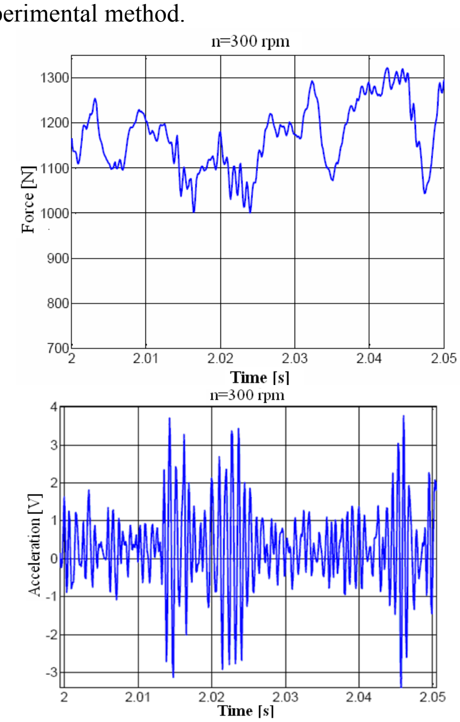

Fig. 3. *The equipment used for the stability control*

Processing each pair of signals by the incorporated stability control system is made according to the following algorithm:

Step 1 - Elimination of the slow time-varying component, separately for each of the two signals.

Step 2 - Scaling the two signals thus filtered.

Step 3 - Fourier Transform of the two signals.

After Fourier transformation the obtained results are similar to the experimental results presented in Figures 4, 5, 6, 7.

Step 4 – Establishing the position of the cutting process towards the dynamic stability limit, analyzing the Fourier transforms of the two signals, based on the comments below.

A first observation is that, in the example considered, the machining system has only one then natural frequency. Moreover, than, in cases where the cutting process is in the instability domain, i.e., at speeds of 500 rpm or higher, the system’s natural frequency is distinguished by clarity, both for the force signal and for the acceleration signal.

On the other hand, in cases where the cutting process is in the stability domain, i.e., for the speeds below 500 rpm, the two signals differently highlight the natural frequency of the machining system. Thus, the force signal does not reveal this at all, for the whole stability domain, while the acceleration signal stability domain divided into two areas. The first area that will be called the sensitive stability is near the limit of stability being characterized by the natural frequency of the machining system, the better highlighted, the more the process is closer to the limit. The remaining area of stability from the second area will be called the insensitive stability, and is characterized by the fact that at both signals, the natural frequency of the machining system does not distinguish.

Step 5 - Determine the state variables, even those that are characteristic of the process of cutting or the machining system, which will act as control variables, and modify them up to the values programmed by the part-program in order to achieve a goal previously established.

In applying the method for online control of the dynamic stability, crossing this step depends on the possibilities available on the machining system, or can be created specifically to control stability. In many practical cases, the width of chip, the cutting speed, and sometimes the chip thickness are the most frequent candidates for the role of dynamic stability control variables.

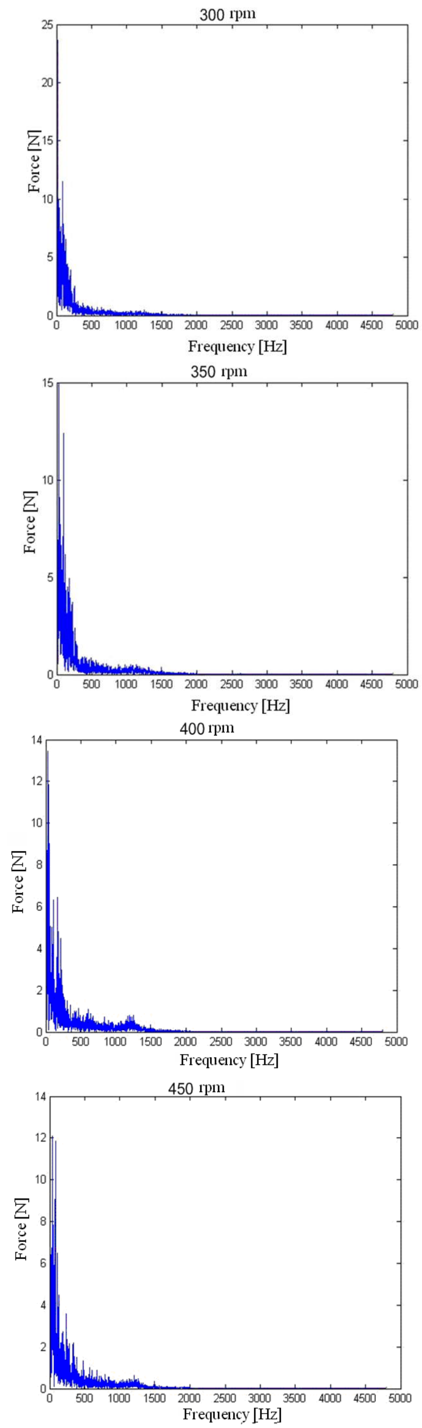

Fig. 4. *Frequency amplitude charts for the force signal of two different spindle speeds for which the dynamic instability phenomenon didn’t occur*

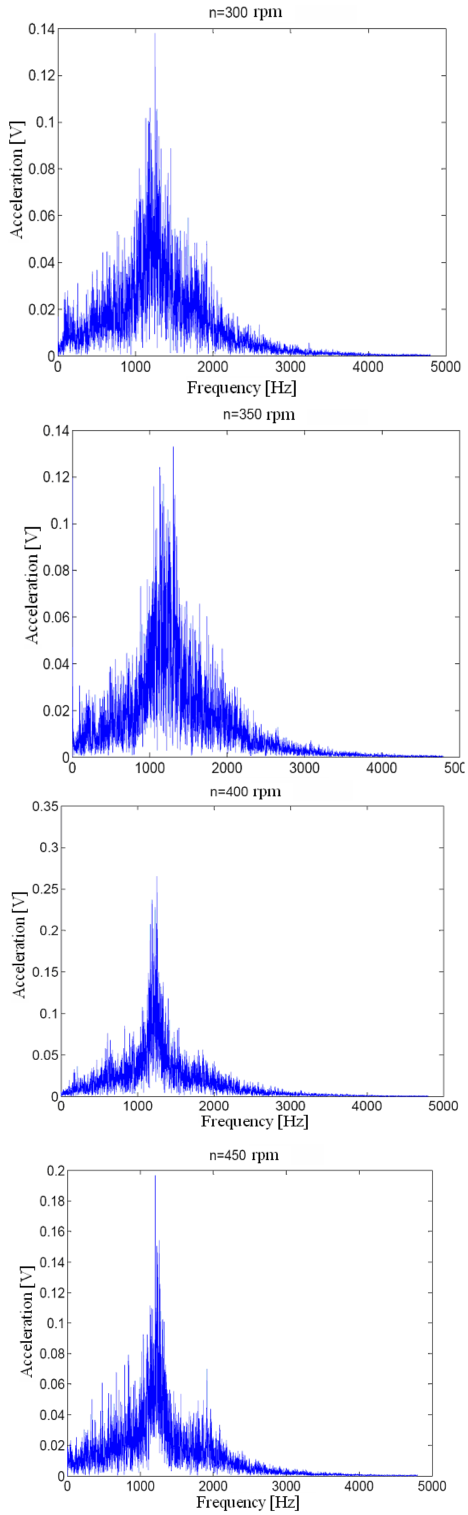

Fig. 5. *Frequency amplitude charts for the acceleration signal of two different spindle speeds*

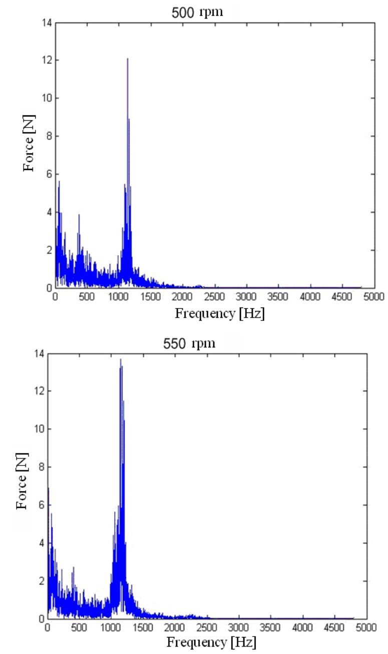

Fig. 6. *Frequency amplitude charts for the force signal of two different spindle speeds*

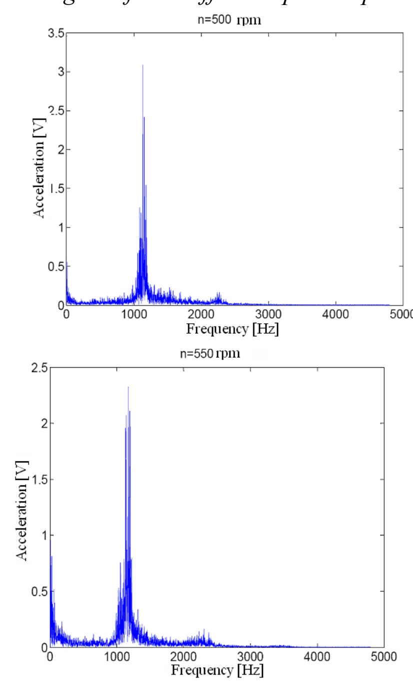

Fig. 7. *Frequency amplitude charts for the acceleration signal of the two different spindle speeds*

For example, figure 8 shows the intersection space of possible values of chip thickness, *a*, chip width, *b*, and the cutting speed, *v*, with two planes *P* and *Q*. Plan *P* is perpendicular to the axis of the chip thickness, *a*, and correspondingly adjusted if the value of the chip thickness is a_0. This plane intersects the surface describing the stability limit, after the line *7-C-8-T-9*. The plane *Q* is perpendicular to the axis of the cutting speed, *v*, and correspondingly adjusted if the value of the cutting speed is v_0. This plane intersects the surface of describing the limit of stability, after the line *10-C-11*.

In order to present an example of crossing this step, consider the plane section P and a cutting process in which the chip thickness and the chip width remain constant at their scheduled values, namely, a_0 and b_0 respectively, while the cutting speed is designated as the variable stability control. During the online control of stability, the current operation point of the machining system moves along *RSTU* line, located in this plan. If we desire to maximize the process productivity, then the operation point must be located on the *ST* segment, as close to the point *T*.

If both the force signal and the acceleration signal, shows the natural frequency of the machining system, then the current operation point in the segment *TU* is located in the area of instability, and the cutting speed should be reduced to bring the operating point on *TS* segment, where the force signal shows no natural frequency of the machining system and the acceleration signal clearly shows this natural frequency.

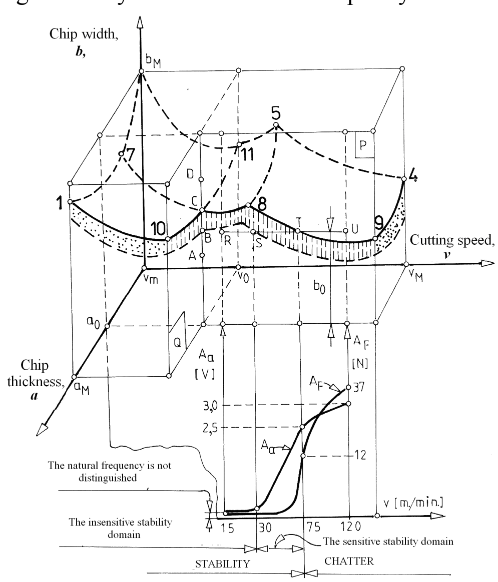

Fig. 8. *Conceptual scheme of the algorithm*

If, any of the two signals does not indicate its frequency, then the current operating point is on the *RS* segment and the cutting speed should be increased until the acceleration signal clearly shows its natural maximum frequency, while the force signal one shows no natural frequency. Thus, the operating point reaches the *ST* segment, near the point *T*.

At the bottom of the *P* plane, the charts concerning the dynamic stability control are shown, going through the signal A_a of the acceleration signal and the amplitude A_f of the force signal corresponding to the natural frequency of the machining system (for the numerical values in the figure, see also figures 4, 5, 6, 7).

A similar example for running the algorithm can be presented if, as a route of the operation point during the stability control is considered the *ABCD* line contained in the *Q* plane. In this example, the control variable is the width chips, *b*, while the chip thickness and the cutting speed remain constant, at their scheduled values a_0, v_0, respectively. By modifying the control variables, the position of the operation point is brought onto segment *BC*, closer to point *C*, thus reaching the desire to achieve the maximum productivity.

6. Conclusion

1. The approach proposed in the paper provides the use of the machining system processing capacity, as far as the concerns the dynamic stability.
2. The control method presented in this paper can be applied for any machining system for which the dynamic instability is represented by self-excited vibrations between the tool and the part.
3. The proposed method allows near optimal control of the machining system stability. The proposed control system requires a small number of service settings, to adapt the changes in the structure and operation of the machining systems.
4. The described control system allows satisfying, both dedicated and flexible machining systems requirements.
5. The experimental test developed in this paper shows the system feasibility.

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