MODELLING OF INFLUENCE OF SOME CUTTING PROCESS PARAMETERS ON CHATTER AMPLITUDE

SUMMARY
Vibrations are an inseparable, and in most cases, undesirable effect that accompanies cutting. They are one of the main causes which limit development of machine tools systems. For this reason, the problems of nature of vibrations are studied in many publications and research. Paper contains the results of model study concerning the influence of some cutting parameters (cutting speed, depth-of-cut, corner radius etc) on chatter amplitude. Characteristics of real process were also presented.

Keywords: cutting process dynamics, cutting process modelling, chatter, tool deflection

MODELOWANIE WYPUWY WYBRANYCH PARAMETRÓW PROCESU SKRAWANIA NA AMPLITUĐę DRSAN

Drgania są nieodłącznym i, w większości przypadków, niepożądanym efektem procesu skrawania. Stanowią jeden z najważniejszych powodów ograniczających rozwój systemów obróbkowych. Z tego powodu stanowią przedmiot badań i publikacji wielu badaczy. Artykuł zawiera rezultaty badań modelowych, dotyczących wpływu wybranych parametrów procesu skrawania (prędkość skrawania, głębokość warstwy skrawanej, promień naroża itp.) na amplitudę drgań. Dla porównania zaprezentowano również charakterystyki rzeczywistego procesu.

Słowa kluczowe: dynamika procesu skrawania, modelowanie procesu skrawania, drgania, odkształcenie narzędzia

1. VIBRATIONS IN CUTTING PROCESS

Turning as a cutting process depends on various factors, such as:
- stereometry of cutting edge and its changes caused by wear,
- terms of process and its changes – deterministic and random,
- stiffness of machine tool system,
- process temperature,
- physical properties of material and its dispersion,
- outer factors depend on machine tool features,
- disturbances.

Those factors impact the process and affect one another, often in a non linear way. The fast development of technique and technology caused the need of building a precise mathematical model describing behaviour of MHWT system. Such model should work on a wide spectrum of parameters also in non linear states. Linear methods in problems of vibration dumping became insufficient. Only nonlinear descriptions of the phenomenon permit of its right explanation and description.

Studies on the cutting process stability and its nonlinear character have already had sixty-year history. It was opened by Arnold’s article in 1946, but the next research done by Tobias and Fishwick (1958), Tlsty and Polacek (1963) and Merrit (1965) was needed to understand the sources of chatter during cutting. They proposed an orthogonal model of turning. Those simple models cannot be used for the precise forecast of the process stability, but researchers and engineers used it with a great success by simple adjustments based on intuition and experience (Weck and Altintas 2004).

2. GENERATION AND INFLUENCE OF VIBRATIONS ON A MACHINE TOOL
   – CUTTING PROCESS SYSTEM

The typical sources of vibration are the spindle drive, the work environment, moving and sliding elements, and the cutting process itself (chatter) (Nayfeh et al. 1965). Vibrations generated in cutting process can be classified as follows (Dmochowski 1983):
- Vibrations independent of cutting process
  • vibrations forced by other machines (transmitted by fundaments), unbalanced rotating parts, elements doing to-and-from motion, kinematical inaccuracies of power transmission,
  • vibrations caused by periodic variable stiffness of machine toll parts, for example shifts with splineway,
  • relaxation oscillation – appears in low stiffness feed mechanisms when high friction force occurs in those mechanisms.
Vibrations independent of cutting process are not significant for the point of view of this article and they won’t be discussed widely.
- Vibrations dependent of a cutting process:
  • free vibrations,
  • vibrations forced by a variable cutting force,
  • self-excited vibrations.

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3. SELF-EXCITED VIBRATIONS
IN CUTTING PROCESS

Self-excited vibrations are the most frequent and unfavourable vibration phenomenon characterised by strong, large amplitude of vibrations of the tool in relation to the workpiece and depends on the process type (Gradišek et al. 1998). This kind of vibrations is mostly considered in cutting process models. There are two main reasons of this situation:

- they exert the biggest influence on cutting process, because they are “closest” to cutting process,
- they are relatively easy to model.

An effort to consider the other kinds of vibrations usually leads to very complicated and non-realistic models.

The most significent features of self-excited vibrations are (Dmochowski 1983):

- that they are caused by periodic force induced by vibrations and fading with them,
- energy wastes caused by damping are persistently filled by an energy source (motor). For this reason amplitude can increase or keep on constant value, even when system was dumped.

Self-excited vibrations have two forms: almost harmonic vibrations, or relaxation vibrations (Dmochowski 1983). Almost harmonic vibrations have form nearing sinusoidal and frequency close to the system free vibration frequency. Such vibrations are frequent in the main motion mechanism of machine tools. They can be observed as the vibration of (a) cutting tool. Relaxation vibrations can be characterised by a non sinusoidal course, sometimes also discontinues of motion. Amplitude is independent of load; frequency is clearly different from natural frequency. Relaxation vibrations occur in feed mechanisms in presence of low feed values, causing non-uniform, stepwise movement.

Main causes of self vibrations are:

- Cutting force dependence on the area of cut. When vibrations are triggered off by any accidental, even short-lived, force, the area of cut changes and along with it the value of the cutting force. Cutting force is oscillating about \( F_D \) value that fulfils static cutting conditions. In a simple mass-elastic system with two degrees of freedom the top of edge marks an elliptic curve in the immobile co-ordinate system. The area closed inside that curve correspond to energy delivered to the system during one period of the vibrations for maintain vibrations (pumped energy) (Dmochowski 1983).
- Changes of the area of cutting caused by waviness of the surface machined during the previous tool pass. In following passes the tool machines the material layer with various thicknesses. For this reason, the cutting force periodically changes, which causes derivative vibrations called regenered vibrations (Dmochowski 1983).
- The Cutting force dependence on the cutting speed. This dependence is based on the decrease of the cutting force during the increase of the cutting speed phenomenon.

Blade vibrations are algebraically added to the cutting speed and cause it pulsations. That entails the changes of the cutting force and maintenance of self-excited vibrations (Dmochowski 1983).

Variations of friction force between tool and workpiece, especially on a rake surface (Dmochowski 1983; Grzesik 1996).

4. REGENERATIVE EFFECT DURING TURNING

One of the most important reasons of self-excited vibrations is regenerative effect (Gasiński and Jabłoński 1994). It enables taking into consideration the state of process in present and previous moment (while turning – revolution), considering thus 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 1983). The Depth of the cut value is strongly affected by a phase shift between the previously made waviness and the current dislocation in the cutting point. On the other hand, amplitude depends on dumping in the process – machine tool system (Fig. 1).

![Fig. 1. Regenerative effect as a reason of tool vibrations](image)
The change of the cutting force in the moment $t_1$ causes fading of free vibrations between the workpiece and the tool. The result of this vibration is a wave on the machined surface in the moment $t_2$. After the full revolution of the workpiece in the moment $t_3$, the cutting edge starts machining the waved surface. The changes of the cutting force connected with such conditions stimulate vibrations of the system. For the specific cutting width, the dumping in the system becomes insufficient to turn out the vibrations and the process becomes unstable in the moment $t_4$. Owning to the fact, that the vibrations are maintained by the machining of the previously waved surface, such effect is called the machine trace regeneration effect.

5. METHOD

In doctor thesis (Jabłoński 1998) and paper (Jabłoński 1997) the model of cutting process dynamics was presented. It can be a starting point for multidirectional analysis concerning the cutting phenomenon and geometrical surface layer condition after cutting. The main model assumptions were as follows:

- cutting process is analysed for turning case,
- cutter is the only deformable element,
- cutter is a vibrating beam excited by cutting force,
- regenerative effect is considered,
- cutting force is modified by a function of dynamical limit feed rate dumping,
- all model parameters and variables are normalised to nondimensional form.

Model allows to obtain different characteristics, depending on research direction: time series of state variables, spectral power density and autocorrelation functions or more sophisticated dynamical dependents (Lyapunov exponents, Poincaré section, circle map etc).

As a one of study proposals the simplifying method of stability evaluation was proposed. As a measure of stability an amplitude of tool deflection was assumed.

For the research the following algorithm was proposed (Fig. 2):

- from the time series of tool deflection in thrust direction the part including last 50 revolutions of workpiece was selected,
- then a mean value of this course was calculated and substracted from all registered points of series to obtain a characteristics around zero,
- for series modified in this way a maximum value of series was registered as a amplitude.

![Fig. 2. Calculating of tool deflection amplitude as a measure of process stability](image-url)
6. RESULTS

For verification of model assumptions the simulations to characterize influence of cutting parameters on stability of cutting process were provided. The amplitude of tool deflection in thrust direction as a measure of process stability was assumed. In Figure 3 dependence of amplitude on rotational speed of spindle (cutting speed) was illustrated. On a graph a range corresponding with 1000–1800 rpm in which the simulated process is less stable one can observe. For bigger and lower values of rotational speed, the amplitude of tool deflection is smaller. For comparison, the known characteristics of similar dependence (for constant diameter rotational speed is proportional to cutting speed) is presented in Figure 4 (Dmochowski 1983). The qualitative convergence is visible especially for bigger values of tool entering angle $\kappa_r$.

In Figure 5 another dependence was presented. In this case increasing of depth-of-cut value causes lower stability (bigger amplitude of tool vibrations). The same dependence, known from specialist literature, one can observe in Figure 6 (Dmochowski 1983). The very good convergence between both characteristics is evident.

The graphs presented above show an influence of some cutting parameters on amplitude of tool vibrations i.e. stability of process.

The following characteristics illustrate dependence between some tool features and process stability.

In Figure 7 the influence of corner radius for entering angle $\kappa = 90^\circ$ on modelled amplitude. The positive impact of radius on stability of process is visible. It result from additional friction force generated on round corner surface and increases energy dissipation of cutting process.
In the last Figure 8 a dependence of tool stiffness on tool deflection amplitude for two values of entering angle was presented. According to presumption, decreasing of system stiffness negatively affects on process stability. In addition one can to affirm that cutting is more stable for lower value of entering angle ($\kappa = 75^\circ$).

![Graph of tool stiffness vs tool deflection amplitude](image)

**Fig. 8.** Influence of tool stiffness on amplitude of tool deflection for simulated process

7. CONCLUSIONS

Results presented in the paper allow formulate a few conclusions. Proposed model is realistic and relatively easy to use. The important problem is that solution of the model equations is possible only in numerical way. It causes necessity of applying procedures of numerical integration. Sometimes it can be a source of computational errors.

According to model assumptions, taking into consideration only vibrations caused by regenerative effect occurs correct and enables realistic and efficient research. The dependences of tool deflection amplitude were chosen to the analysis as considered direction, the thrust direction was applying. Tool movement in this direction causes the biggest changes on workpiece surface.

Presented characteristics have confirmed the correctness of model assumptions. The results obtained by simulation occurred to a large extent consistent with results presented in specialist literature. On graphs the qualitative convergences and quantitative proportions are clearly visible. According to expectations and results of previous study:

- amplitude of tool deflection increases in any range of cutting speed – outside of this amplitude gets lower,
- bigger values of depth-of-cut causes increasing of tool deflection amplitude.

Moreover the results of simulation shows that the amplitude of tool vibration decreases while corner radius increasing. The lowest amplitude one can obtain for corner radius equal 2 mm, then amplitude increases again.

Finally, bigger amplitude of tool deflection (lower stiffness) causes bigger tool vibrations.

References


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