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milling process,
chatter regenerative model

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CHATTER IN MILLING OF COMPOSITES: SIMULATIONS AND DIAGNOSTIC

The study focuses on the problem of milling stability, specially dedicated for materials with heterogeneous mechanical properties like composite materials where specific cutting force depends on fibre location and orientation. Classical model of regenerative milling is completed by adding a harmonic function which represents a change of specific cutting force. Finally, an influence of specific cutting force modulation on process stability is presented and vibrations analysis is performed.

1. INTRUCTION

Nowadays, composite material are more and more popular mainly because of its low mass and high strength. On the other hand good mechanical features can render difficult machining specially when a matrix is carbon or glass fibres reinforced. Vibrations during cutting process called chatter, result in low quality of final surface and quite often accelerate tool wear. Dry friction [Wiercigroch et al., 2001] and regenerative effects [Stepan G., 2001], [Faassen R.P.H. et al., 2003], [Fofana M.S., 2002] are often causes of chatter. The former is typical for conventional cutting, the latter mostly for high speed machining (HSM). Machining with high speed is one of key aspect of the modern technologies, which enables to increase efficiency, accuracy and quality of workpiece compared to conventional cutting.

Usually, regenerative models of HSM of metal alloys are quite well known (e.g. [Deshpande et. al., 2001], [Gradisek et. al., 2001], [Insperger et. al., 2003]) but as far as composite materials are concerned cutting models are still being developed. It arises from the lack of detailed specification of composite materials, their mechanical properties which are necessary to obtain the proper stability lobe diagram (SLD). Nowadays, publications which are concerned with composite material machining, frequently focus on tool wear [Conceicao et. al., 2002], [Davim et. al., 2001] methods of avoiding delamination [Davim et. al., 2005]. The investigations of composite material machinability refers both to carbon-fiber

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or glass-fiber reinforced materials [Davim et. al., 2004], [Langella et. al., 2005], [Ramulu et. al., 2003] and metal matrix composites [Zhu et. al., 2005].

As far as tool wear is concerned, diamond tools are the most suitable for use in finishing turning of carbon-carbon composite. In rough turning, the carbide tools can be used but with some restrictions parameters. Tool flank wear is the least for high speed cutting, in the range from 500 to 800 m/min [Ferreira et al., 2001]. One of interesting approaches is presented in [Ramulu et. al., 2003] where the effect of fibre orientation on the normalized frequency spectrum in orthogonal cutting glass fibre reinforced polyester (GFRP) is analysed.

Thus, taking into account achievements in this field, there is a lack of comprehensive study of modelling of composite materials cutting. Therefore, this paper proposes a simple 1 degree of freedom (1DOF) model but adjusted to composite materials such as Glass Fibre Reinforced Polymer (GFRP) or Carbon Fibre Reinforced Polymer (CFRP). With help of the model, stability diagrams are performed and next analysis of vibrations is done.

2. MODELLING OF MILLING

Here, one degree of freedom (1DOF) regenerative model of EPMC-CF milling is developed on the basis of paper [Insperger et. al., 2003]. A tool is modeled as 1DOF oscillator (Fig. 1a) with undamped natural frequency $\omega_0 = \sqrt{k/m}$, where k is the stiffness, m is the reduced mass of tool and c denotes the damping coefficient. The tool rotates with the constant angular velocity Ω (or rotational speed $n=30\Omega/\pi$) and cuts workpiece which moves with velocity f_t (feed per tooth). The cutting force acting on the active j-tooth can be taken apart on the tangential (F_{jt}) and normal (F_{jn}) component:

$$\begin{aligned} F_{tj} &= K_t a_p h_j^{\kappa} \\ F_{nj} &= K_n a_p h_j^{\kappa} \end{aligned} \tag{1}$$

where K_t and K_n are specific cutting force, usually estimated that K_n = 0.3 K_t, [Insperger et. al., 2003] a_p is the depth of cut. The chip thickness h_j is described as static by equation:

$$h_j = f_t \sin\varphi_j \tag{2}$$

where, φ_j is the rotation angle of tooth j, that means the angular tool position φ_j can be expressed by angular velocity Ω, the angle between two subsequent teeth $\vartheta = 2\pi/z$, (z is number of teeth of the cutter):

$$\varphi_j = \Omega t + j\vartheta, \qquad j = 0,1,...,z-1 \tag{3}$$

Dynamic chip thickness, when the regenerative effect is added, can be expressed:

$$h_j = \left(f_t + x(t) - x(t-\tau) \right) \sin\varphi_j \tag{4}$$

where f_t is the feed per tooth, $\tau = \frac{2\pi}{z\Omega}$ is the tooth pass period.

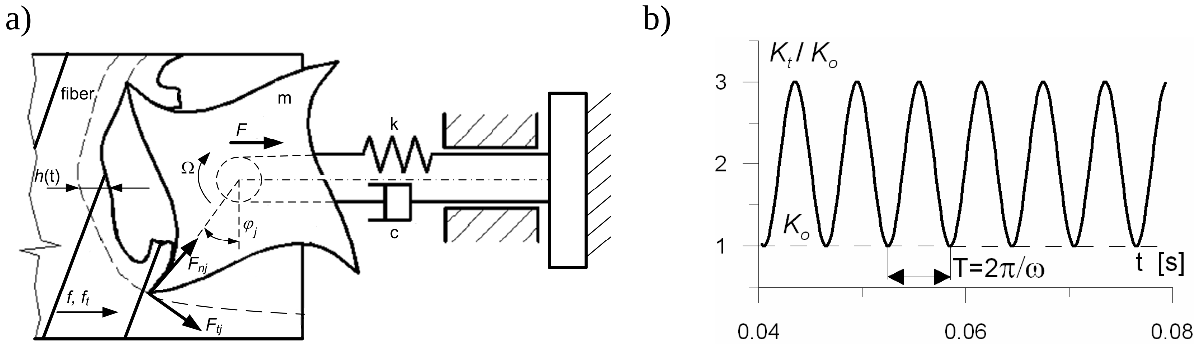

Fig. 1. One degree of freedom model of regenerative milling (a); Change of specific cutting force K_t (b)

The coefficient κ is used in various papers and its value is estimated between 0.75 and 0.9. Then, the cutting force F acting on j-th tooth in the x direction is described as follows:

$$F_j = \left(F_{nj}\sin\varphi_j + F_{tj}\cos\varphi_j\right) g_j \tag{5}$$

g_j is equal to *1* if the j-th tooth is active and *0* if it is not or when the chip thickness h_j is negative. The tooth is in cut if $\varphi_s \leq \varphi_j \leq \varphi_e$, where φ_s and φ_e are the start and exit angles, respectively. This function for the radial depth of cut (a_e) equals half the tool diameter (a_e =6 mm) is given by:

$$g_j = H(sin\varphi_j)\cdot H(cos\varphi_j - cos\varphi_e) \tag{6}$$

For all teeth equation (5) takes form:

$$F = \sum_{j=1}^{z}\left(F_{nj}\sin\varphi_j + F_{tj}\cos\varphi_j\right) g_j \tag{7}$$

Differential equation of motion for 1DOF model presented in Fig.1a can be written as:

$$m\ddot{x} + c\dot{x} + kx = F \tag{8}$$

Periodically change of cutting force, observable in some papers (e.g. [Rusinek 2010]), during cutting of materials reinforced by glass or carbon fibers results from the change of active cutting edge number but, if we assume that the workpiece is heterogeneous some change of specific cutting force is also possible. The specific cutting force considerably depends on fiber orientation as well. In that case, it can be assumed that tool motion is not rectilinear. Then, relative fiber position in relation to feed direction varies during machining.

That can produce specific cutting force modulations (Fig. 1b), therefore in this study the specific cutting force K_t may be expressed as a simple harmonic function:

$$K_t = K_o\left(b + \sin\omega t\right) \tag{9}$$

where: frequency ω denotes angular frequency of specific cutting force, b is a constant (b=2) and K_o is a minimal specific cutting force. The influence of parameter ω will be comprehensively analyzed in further section.

3. MILLING STABILITY

In this section, the model of milling process proposed in the previous section is used for the purpose of stability analysis which is performed in high speed machining (HSM) conditions (1 krpm<n<20 krpm). The differential equation (8) describes the dynamics of the system presented in Fig. 1a. The equation of motion is solved with the help of Matlab – Simulink package using parameters as follows: m = 2.586kg, k = 2.2 x 10^6 N/m, c = 18.13Ns/m, K_o = 1.9 x 10^8 N/m$^{1+\kappa}$, f_t =0.05 mm, κ=0.8, j=1, a_e=6 mm. Rotational speed (n) and axial depth of cut (a_p) are parameters which are analyzed. The method of 4th order Runge – Kutta is used for numerical integration. For ease of numerical computations, we have replaced the discontinuous Heaviside function H(.) in Eg. (6) by their smooth approximations using the function given by: $H(x) = 1/(1+e^{-\sigma x})$, where σ is a large number; in our computation we assume $\sigma = 500$.

As a stability criteria during numerical simulations a critical value of vibrations amplitude is applied. When vibrations amplitude is greater than A_{cr} = 5 mm the process is classified as unstable. On the basis of simulations results the stability lob diagrams (SLD) is created for three cases. First, when the specific cutting force K_o=K_t, (ω=0, Fig. 2) next for slow change of specific cutting force (ω=10π rad/s, Fig. 3) and fast change (ω=100π rad/s, Fig. 4) which does not have practical application but is an interesting case for theoretical investigation. The shaded areas on SLD mean unstable region. For classical approach K_o=K_t, (Fig. 2) the unstable lobs are narrower than in the case of the specific cutting force change, what is more the critical depth of cut for K_o=K_t has higher value (about 1mm). Thus, additional modulation of specific cutting force destabilize the process because of bigger specific cutting force. When the period of change T is long enough (slow change of K_t, Fig. 3) vibrations can rise significantly in the time. While, for bigger ω (short period T) the unstable lobs are smaller in comparison with previous case. Generally, the cutting force modulation increases the instability region specially when modulation frequency is relatively small. That may have big meaning during milling materials like composites that have various strength properties (specific cutting force) in different directions.

Looking at the phase portraits (Fig. 5) obtained for unstable cutting (a, c) and stable (b, d) it can be noticed that vibrations in unstable (shaded) region have huge amplitude and are quasi-periodic while, for cutting parameters which are placed in stable regions, vibrations usually are sub-harmonic. This observation can be useful to cutting process control. A control system could analyse kid of vibrations and decide whether process is stable or not, if not a controller should change cutting parameters.

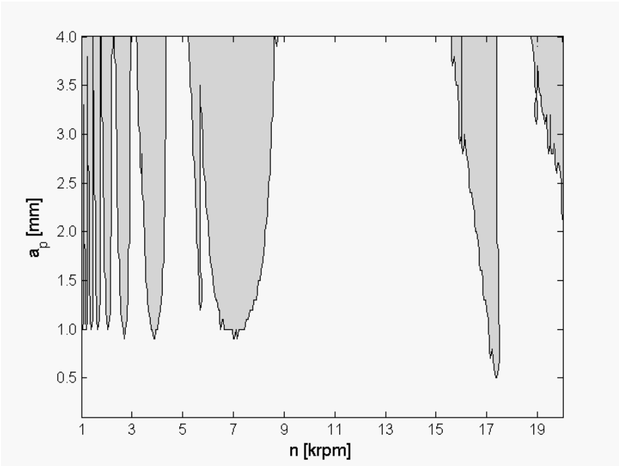

Fig. 2. Stability lobs diagram for specific cutting force $K_o=K_t$ $(\omega=0)$

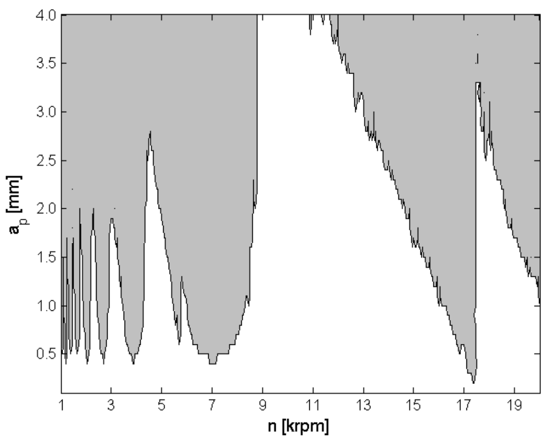

Fig. 3. Stability lobs diagram for changing specific cutting force with frequency $\omega=10\pi$

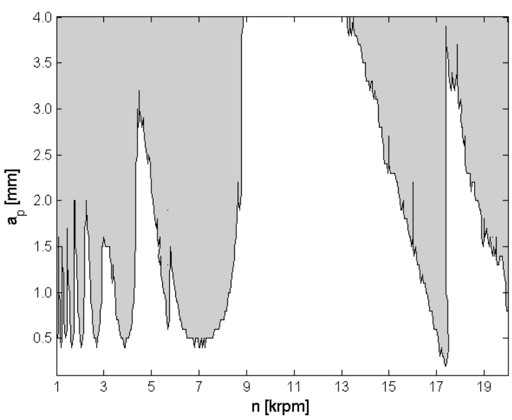

Fig. 4. Stability lobs diagram for changing specific cutting force with frequency $\omega=100\pi$

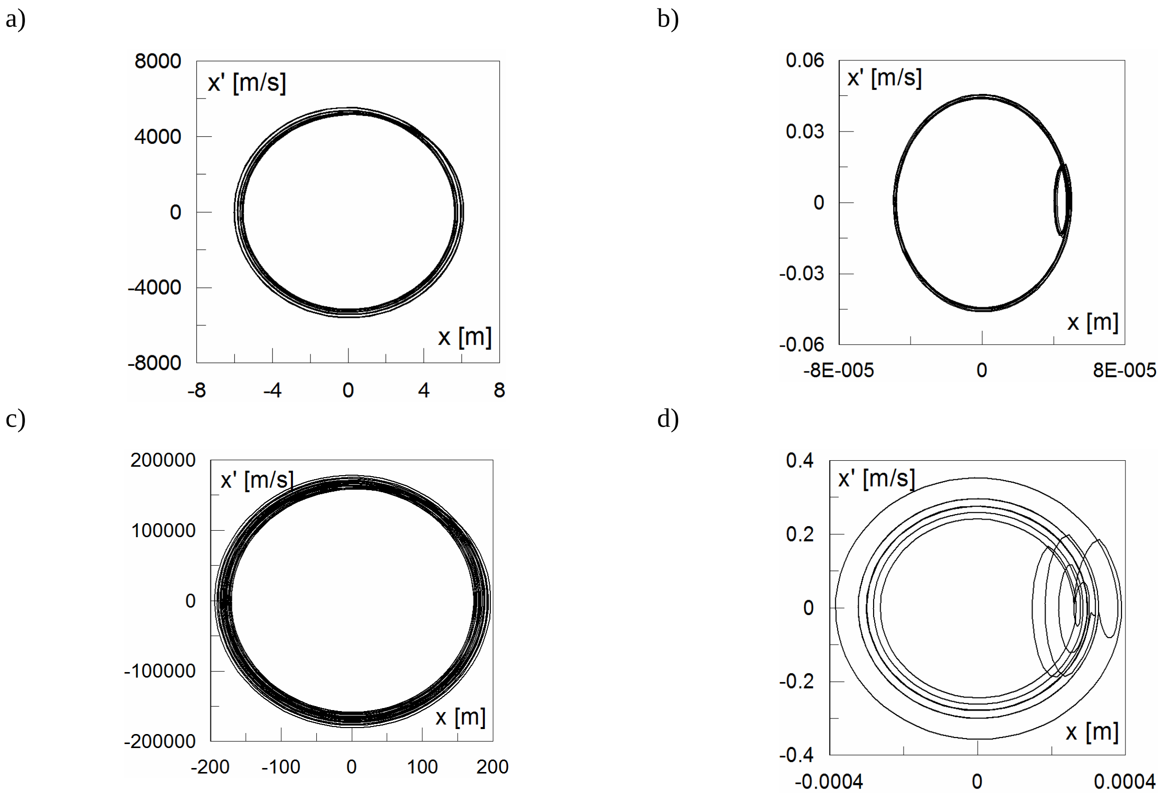

Fig. 5. Phase portraits for unstable milling (a, c) and stable milling (b, d). Cutting parameters: a) n=7 krpm, a_p=2 mm ω=0; b) n=14 krpm, a_p=2 mm ω=0; c) n=7 krpm, a_p=2 mm ω=100π; 4) n=14 krpm, a_p=2 mm ω=100π

4. CONCLUSIONS

The study presents the problem of milling materials which are heterogeneous or have changeable resistance during cutting. Classical regenerative one degree of freedom model is modified by adding specific cutting force modulation. This modulation can be a source of additional instability in the system that is visible in the stability lobs diagram. Interestingly, the instability depends naturally on the specific cutting force magnitude and also on its frequency. The slow change of the specific cutting force is more dangerous than fast one. Analysis of vibrations reveals that process instabilities can be identify on the basis of phase portraits of displacement. In the future work author plan to introduce recurrence plots technique to find efficient method for instabilities detection and for milling process stabilizing.

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