Chatter control in the milling process of composite materials

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Abstract. In this paper, a model of the milling process of fibre reinforced composite material is shown. This classical one degree of freedom model of the milling process is adjusted for composite materials by variable specific cutting forces, which describe the fibre resistance. The stability lobe diagrams are determined numerically. Additionally, to eliminate the chatter vibration, small relative oscillations between the workpiece and the tool are introduced. Basing on numerical simulations the range of amplitude and the frequency of excitation is found for chatter reduction.

1. Introduction
A composite material consist of two or more materials that results in better properties than when the individual components are used alone [1]. The aerospace and aeronautical industries have been major users of composite technology in the last decades. Composite materials provide distinctive advantages in the manufacture of advanced products because of attractive features such as simultaneous high strength and light weight. There are a large number of various composite materials used in aircraft, automotive, aerospace and many other industries. In modern engineering high demands are being placed on components made of composites in relation to their dimensional precision as well as to their surface quality. As a result of potential applications there is a great need to understand the questions associated with the machining of composite materials. They are more difficult to machine than classical materials mainly because they are anisotropic, nonhomogeneous and are reinforced by hard glass or carbon fibres [3]-[4]. That leads to fast tool wear [5]. Anisotropic and inhomogeneous material properties create problems during machining of composite materials. The cutting forces depend on the fibre direction of the laminate. Machining forces and finish surface quality may change depending on the direction of cutting. In addition, the rubbing effect of the deboned particles on the machined surface degrades the surface quality of the product [6], [7]. Unwanted self-excited vibrations between the tool and workpiece, called chatter, are a primary cause of surface finish roughness in cutting both classical and composite materials. During the machining of composite materials, additional problems may arise especially when the matrix is carbon or glass fibre reinforced.

The primary aim of this article is the reduction of chatter vibrations during composite material milling. The paper is based on a classical one degree of freedom milling model with a chatter control system (CCS) which generates small relative vibrations between the workpiece and the tool in order to improve cutting conditions.
2. Modelling of the milling process

2.1. Modelling of milling process with active workpiece vibration

In the milling process, material is removed from a workpiece by a cutting tool, which rotates with speed $\Omega$ (in rpm). A schematic representation of the milling process is shown in Fig. 1. The cutting force $F_j$ acting on jth tooth ($j=0,1,\ldots,z$) in the $x$ direction is represented by tangential ($F_{tj}$) and normal ($F_{nj}$) component

$$F_j = \left( F_y \sin \varphi_j - F_{nj} \cos \varphi_j \right) g_j,$$

(1)

where $z$ represents the number of tool teeth, and $g_j$ defines when $j$-th tooth is active. Tangential and radial cutting force actions on the tool are generally proportional to the axial depth of cut ($a_p$) and chip thickness ($h_j$)

$$F_y = K_t a_p h_j (t)^\kappa, \quad F_{nj} = K_n a_p h_j (t)^\kappa,$$

(2)

where $K_t$ and $K_n$ are specific cutting forces which depend on the cutting material properties, depth of cut $a_p$ and fibre orientation. The coefficient $\kappa$ also depends on the material, and is usually estimated about 0.8-1[8].

The chip thickness $h_j(t)$ is a function of the feed of the cutter $f_z$, tool vibrations (regeneration effect) and the active excitation of workpiece $F(t) = q \sin (\lambda t)$. The actual chip thickness is

$$h_j = \left[ f_z + x(t) - x(t - \tau) \right] \cos \varphi_j - q \sin (\lambda t),$$

(3)

where the tooth passing period is $\tau = 60/z\Omega$. Parameters $q$ and $\lambda$ are responsible for active vibration control. This workpiece excitation in the real system can be caused by piezoelectric stack actuators. The step function $g_j$ is defined in order to check whether the tool is in cut or not:

$$g_j(\varphi_j) = \begin{cases} 1, & \varphi_s \leq \varphi_j \leq \varphi_e \text{ and } h_j > 0 \\ 0, & \text{elsewhere} \end{cases}.$$  

(4)

Where the conditions described in Eq. (4) are realized by Heaviside functions. In order to calculate the total milling forces, the number of teeth ($z$) on the cutter and the radial depth of cut ($a_r$) and diameter of cutter ($d$) must also be known. Then, for down milling the entry ($\varphi_s$) and exit ($\varphi_e$) angles are defined

$$\varphi_s = \arcsin \left( \frac{d - 2a_r}{d} \right), \quad \varphi_e = \pi / 2.$$

(5)

The equation of motion, for one degree of freedom milling model can be written as

$$m \ddot{x} + c \dot{x} + k x = a_p h(t) \sin \varphi - K_n \cos \varphi g_j,$$

(6)

where $k$, $c$ and $m$ are stiffness, damping and mass obtained by modal tests [8].
2.2. Fibre orientation effect
Because of the anisotropic nature of fibre composites, distinctly different cutting mechanisms have been observed depending on the fibre orientation with respect to the direction of tool motion [9]-[11]. The peculiar aspect of cutting with a rotating tool such as in milling is that the fibre orientation angle $\theta$, is not constant, but varies continuously with cutting edge position around the cutter axis [12]. Fig. 2 shows the definition of fibre orientation with respect to the angle of tool rotation.

![Fig. 2. Fibre orientation of unidirectional laminate for down milling process.](image)

In our example, for down milling of a unidirectional laminate the fibre direction angle is defined by $\psi = 45^\circ$. The temporary angle $\theta$, is measured clockwise from the cutting velocity vector ($V$) to the location of the teeth. For the case shown in Fig. 2, it can be written that

$$\theta = \frac{\pi}{2} - (\varphi - \psi). \tag{7}$$

The specific cutting forces $K_n$ and $K_t$ corresponding to these fibre orientations are shown in Fig. 3a [12]. The specific cutting forces rise gradually with an increase in fibre orientation and reach a maximum between $60^\circ$ and $120^\circ$. Interestingly, for the fibre direction angle $\psi = 45^\circ$ the specific cutting force is higher if the edge is near the exit (then the chip thickness is smallest –down milling, Figure 3b).

![Fig. 3. Variation of specific cutting forces $K_t$ and $K_n$ depending on fibre orientation $\Theta$ (a), and tool position $\phi$ for $\psi = 45^\circ$ (b) [12].](image)

| Coefficient | $K_n$ [N/mm$^2$] | $K_t$ [N/mm$^2$] |
|-------------|-----------------|-----------------|
| $a_0$       | 30.5840         | 137.1059        |
| $a_1$       | 0               | -536.5678       |
| $a_2$       | 0               | 1115.3922       |
| $a_3$       | 109.6388        | -786.1277       |
| $a_4$       | -76.3806        | 224.6042        |
| $a_5$       | 13.2425         | -22.5474        |
| $n$         | -0.6937         | -0.7329         |

Table 1. Coefficients of equation (8).
The mathematical function which characterises the specific cutting forces is formulated on the basis of [12] in the form

\[ K_{n,t} = a_n^p \left( a_0 + a_1 \theta + a_2 \theta^2 + a_3 \theta^3 + a_4 \theta^4 + a_5 \theta^5 \right), \]  

where \( a_0, a_1, a_2, a_3, a_4, a_5, \) and \( n \) are regression model coefficients and are given in Table 1. The angle \( \theta \) in the equation (8) is in radians. The model is verified by experiment in paper [12].

3. Results and discussion

3.1. The influence of fibre orientation on milling stability

During the machining the problem of dynamic stability is very important from the practical point of view[13]. Therefore, section a stability analysis is performed for high speed machining (HSM) conditions (100 rpm<\( \Omega <20 \) krpm). The governing equation (6) with (7) and (8) is solved with the help of the fourth order Runge-Kutta method with a fixed time step of 0.0001. Stability lobe diagrams (SLD) have been generated using parameters obtained from experimental modal tests of a real spindle-tool system (CNC milling machine Blue Bird MG6037PKK). Based on the modal analysis performed on the milling machine with the one flute PCD end cutter (Cuttech, radius of 6mm), the modal parameters are: \( m=0.8kg \), \( k=2.22 \times 10^7 \) N/m, \( c=57.3Ns/m \). The radial depth of cut \( a_p=6mm \), feed \( f_z=0.03mm/tooth \), number of teeth \( z=1 \) and exponent \( \kappa=0.9 \). To identify the region of process stability, on the basis of numerical simulations, an amplitude criterion is introduced, namely if the amplitude is greater than 1mm we classify the process as unstable. A similar criterion has been used in paper [13], where SLD obtained by simulation is compared with the results obtained by commercial software CutPro9. Additionally, in papers [13] and [14] new indices to detect unstable motion are proposed. In Figure 4a the stability lobe diagram (SLD) for a classical model with constant specific cutting forces is shown. The black area denotes unstable milling parameter ranges, but the white colour indicates ranges of parameters for stable machining.

Fig.4. The classical SLD obtained for constant values of \( K_t=7500 N/mm^2 \) and \( K_n=4000 N/mm^2 \) (a), SLD obtained for composite model described by eqs. (7) and (8) for \( \Psi=45^\circ \) (b)

A numerical stability lobes diagram has been done by point-by-point investigation of a grid in the parameter space consisting of the spindle speed resolution 50rpm and depth of cut resolution 0.1mm. The SLD presented in Fig. 4a and 4b are much different. The chatter frequency seems the same, however the critical depth of cut for classical model equal about 1mm (Fig.4b), but for composite materials is shifted down and equal 0.1mm. The results suggest that the classical approach to determine the stability of cutting process fails. Interestingly, that for composite material exist regions, where the cutting process with large depth of cut is possible.
3.2. Control of chatter vibration

In the literature several methods are proposed to counteract chatter. Generally, components based on the integration of mechatronic systems into the machine structure are the most promising [15]. Martinez et al. [16] demonstrated the feasibility of piezoelectric stack actuators in chatter reduction.

![Fig.6](image)

*Fig.6.* Time history of tool vibration without activation of workpiece (a) and with activation \( q=0.5\text{mm} \) and \( \lambda=20000\text{rad/s} \) (b) for \( a_p=0.5\text{mm} \) and \( \Omega=6\text{krpm} \) and fibre orientation \( \Psi=45^{\circ} \).

![Fig.7](image)

*Fig.7.* Two parameters space plot: amplitude and frequency of workpiece excitation, \( \Omega=6\text{krpm} \) (a) and \( \Omega=18\text{krpm} \) (b), for \( a_p=0.5\text{mm} \) cutting parameters for fibre orientation \( \Psi=45^{\circ} \).

In *Fig.6*, the time history of tool vibrations, for two cases, is presented. The first time course (*Fig. 6a*) is obtained for \( \Omega=6\text{krpm} \) and depth of cut \( a_p=0.5\text{mm} \) (circled point by solid line in *Fig. 4b*). The amplitude of vibration without the chatter control system (CCS) reaches a value of about \( x=3\text{mm} \), but if we activate the control system, the vibrations amplitude is below \( 1\text{mm} \) (*Fig.6b*). This denotes that the machining process is being stabilized. The main problem is how to choose parameters of CCS. Therefore, *Fig. 7*, presents the two parameter space plot: amplitude and frequency of excitation (\( \lambda-q \)). For the unstable point from *Fig.4b* \( (a_p=0.5\text{mm}, \Omega=18\text{krpm}) \) CCS works correctly if parameters \( \lambda \) and \( q \) are selected from white region *Fig. 7a*, while \( \lambda-q \) from the black regions does not stabilize the milling process. An activation of CCS for stable cutting parameters \( a_p=0.5\text{mm}, \Omega=6\text{krpm} \) (*Fig.4b*) can destabilize the process if \( \lambda \) and \( q \) are selected from black regions (*Fig. 7b*). This is very important from the engineering point of view because CCS can eliminate chatter vibration or on the contrary – generate it. Therefore, the use of CCS must be carefully applied.
4. Conclusion and final remarks
Determination of the cutting process stability of typical commonly used materials can be calculated quite easy. The problem arises when the workpiece is made of material which has heterogeneous properties e.g. composites. Then the classical approach fails, and commercial software does not have properties for heterogeneous materials. Therefore, analysis of composite cutting materials is important from the practical point of view. The presented model can be used to determine the stability chart of the machining process.

To improve the milling process and eliminate chatter vibrations, the CCS is proposed for composites materials. This method should be carefully applied, because the specific parameters of CCS can generate vibrations. Therefore, this method of stabilizing requires detailed verification.

Acknowledgements
The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013), FP7-REGPOT-2009-1, under grant agreement No: 245479. The support by the Polish Ministry of Science and Higher Education-grant no 1471-1/7.PR UE/2010/7-is also acknowledged.

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