Analysis of Chatter Mechanisms in Cutting Process

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Summary. Analysis of a nonlinear two degree of freedom model of a cutting process is presented in the paper. Classical regenerative mechanism of chatter is enriched in an additional friction phenomenon which generates frictional chatter. A goal of the paper is to detect a mutual interaction between the regeneration and frictional effect. The nonlinear model is solved by means of the multiple time scale method. Stability of cutting process is checked in order to determine stability lobes diagrams and to find an influence of friction on the process. Nonlinear behaviour is also examined for different variants of stiffness ratio with the help of bifurcation diagrams where cutting velocity is chosen as the bifurcation parameters. Finally, the maps of chatter amplitudes are presented and new frictional stability lobe diagrams are proposed to analyse an influence of friction.

Introduction

Nowadays, cutting process is still one of the most popular manufacturing method. During machining operations, vibrations called chatter may occur between the workpiece and the tool. This phenomenon generates dimensional and geometrical inaccuracies, a poor surface finish, faster tool wear and reduction of spindle life. Therefore, it is necessary to understand and control chatter vibrations. The regenerative effect is related to the wavy workpiece surface generated by the previous cutting tooth pass. While, the frictional mechanism results from friction force occurring between the tool and the workpiece. Although, trace regeneration and friction are the most important in practical operations there are little papers which consider regenerative and frictional mechanisms together. Friction always exists in real cutting process therefore, excluding this phenomenon is rather a big simplification. Generally, chatter is a dynamic instability that can limit material removal rates, cause a poor surface finish and even damage the tool or the workpiece. Usually in the literature the problem of the regenerative and frictional chatter mechanisms are investigated separately, although friction phenomena exist always in case of a contact problem. Therefore, this approach describes the model of orthogonal cutting both with regenerative and frictional effect. The model of frictional chatter, presented in [3], is completed with regenerative effect. In order to get knowledge about an influence of frictional chatter on regenerative one and complete an mathematical approach, the mathematical model of cutting is developed and solved with the help of the method of the multiple time scales [1, 2]. An explanation of mutual interaction between frictional and regenerative mechanisms is the main purpose of the paper.

Mathematical model

To analyse regenerative and frictional mechanism of chatter, two degree of freedom model of orthogonal cutting is used (Fig.1a). Figure 1b presents the force distribution on the tool edge separately for the rake face and flank face. This is a quite new approach because classical analysis takes into account only the rake face forces or resultant force acting on the tool. Here, the resultant cutting force is distributed on the normal force on the rake N_1 and face N_2 force. The normal forces together with friction between the tool and the workpiece cause the friction force F_1 and F_2 on the rake and the flank face, respectively. This approach of cutting force distribution is presented more detailed in the paper [3]. The normal and the friction force are defined as follows:

$$\begin{gathered} N_1 = Q_o\, a_p \left(c_1 (v_r - 1)^2 + 1 \right) H(a_p) H(v_r), \quad N_2 = K_{con}\, a_p\, H(a_p), \\ F_1 = N_1 \mu_x \left(\operatorname{sgn}(v_f) - \alpha_x v_f + \beta_x v_f^{\,3} \right), \quad F_2 = N_2 \mu_y \left(\operatorname{sgn}(v_r) - \alpha_y v_r + \beta_y v_r^{\,3} \right), \end{gathered} \tag{1}$$

where, Q_o represents the specific cutting force modulus, a_p is the instantaneous penetration of the tool into the workpiece (depth of cut), c_1 is a constant controlling the dependence of the cutting force on the relative velocity between the tool and the workpiece v_r, K_{con} is the contact stiffness and H represents the Heaviside function. Note that the $H(v_r)$ models the loss of contact between the tool and the chip while $H(a_p)$ accounts for the tool coming out of the workpiece. In the friction forces μ_x, μ_y denote the static coefficient of friction between the tool and the workpiece, and the tool and the chip, respectively, α_x, α_y, β_x, β_y are constants which regulate the nonlinear characteristics of the friction forces between the respective surfaces in contact. v_r and v_f are the relative velocities between the tool and the workpiece, and the tool and the chip, respectively and *sgn* represents the sign function. The instantaneous penetration of the tool into the workpiece or the cutting depth a_p can be written in terms of the specified depth of cut a_{po}, the tool motion y and the tool motion one rotation before $y(t-\tau)$ as:

$$a_p = a_{po} - y + \delta y(t - \tau), \tag{2}$$

where, δ equals *0* or *1* when the regenerative effect is switched off or on. Time delay τ is connected with a spindle or a workpiece speed Ω by equation $\tau = 2\pi/\Omega$. The relative velocities between the tool and the workpiece v_r, and the tool and the chip v_f are related to the nominal cutting speed v_o, the shear angle of the workpiece material φ and the tool velocities by:

$$v_r = v_o - x', \quad v_f = v_r \tan\varphi - y'. \tag{3}$$

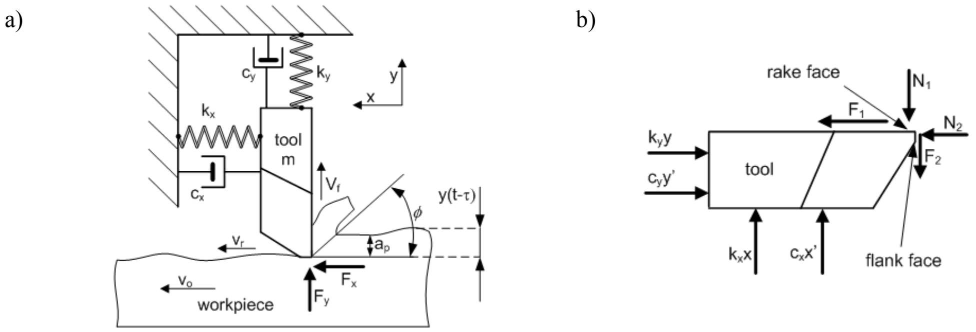

Figure 1: Two degrees of freedom model of orthogonal cutting (a), force distribution on tool edge (b) [3]

The non-dimensional equations of motion is defined in the form:

$$x'' + 2z_x x' + x = f_x, \qquad y'' + 2z_y\sqrt{\alpha}\,y' + \alpha y = f_y, \tag{4}$$

where:

$$\alpha = \frac{k_y}{k_x}, \quad \omega_x^{\,2} = \frac{k_x}{m}, \quad \omega_y^{\,2} = \frac{k_y}{m} = \alpha\,\omega_x^{\,2}, \quad z_x = \frac{c_x}{2m\omega_x}, \quad z_y = \frac{c_y}{2m\omega_y}, \tag{5}$$

and the forces are given by:

$$\begin{aligned} f_x &= q_o\,a_p\left(c_1\left(v_r-1\right)^2+1\right)H(a_p)H(v_r) + k_{con}\,a_p H(a_p)\,\mu_y\left(\mathrm{sgn}(v_r)-\alpha_y v_r+\beta_y v_r^{\,3}\right), \\ f_y &= k_{con}\,a_p H(a_p) + q_o\,a_p\left(c_1\left(v_r-1\right)^2+1\right)H(a_p)H(v_r)\,\mu_x\left(\mathrm{sgn}(v_f)-\alpha_x v_f+\beta_x v_f^{\,3}\right). \end{aligned} \tag{6}$$

Analytical and numerical results

The nonlinear model described by Eq.4 is solved by means of the multiple time scale method. Next to verified analytical result the numerical simulation was performed by using Matlab-Simulink software. Both results are presented as stability lobes diagrams (Fig.2), where cutting velocity v_o, proportional to the spindle speed Ω, is on the horizontal axis and on the vertical axis is cutting resistance q_o. Unstable areas (gray color in Fig.2a) were obtained analytically, while the amplitude value (gray scale in Fig.2b) was also numerically determined. In both cases, a characteristic stable area was observed in the middle of the graph.

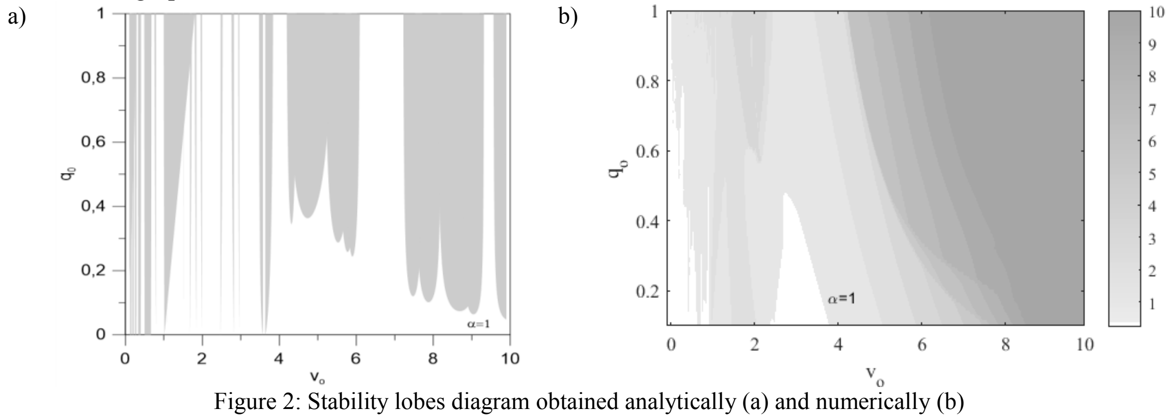

Figure 2: Stability lobes diagram obtained analytically (a) and numerically (b)

Conclusions

The paper presents the results of analytical and numerical analysis of a two degree of freedom nonlinear model. An analytical solution of the model near the primary resonances are obtained by using the method of multiple time scales. The frictional and regenerative mechanisms of chatter are important both acting together and separately. The regenerative effect is stronger for small velocities (rotational speeds) while the frictional one for higher velocities. However, it depends on the workpiece stiffness ratio as well. Friction causes a stabilising effect when regenerative chatter dominates. Regardless the chatter mechanisms the chatter free region can be found in the middle range of analysed velocities.

References

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