11th World Congress on Computational Mechanics (WCCM XI)
5th European Conference on Computational Mechanics (ECCM V)
6th European Conference on Computational Fluid Dynamics (ECFD VI)
E. Oñate, J. Oliver and A. Huerta (Eds)

DYNAMICS ASPECT OF CHATTER SUPPRESSION IN MILLING

RAFAL RUSINEK[*], AMDRZEJ WEREMCZUK[†] AND JERZY WARMINSKI[†]

[*] Lublin University of Technology (LUT)
Department of Applied Mechanics, Mechanical Engineering Faculty
Nadbystrzycka 36, 20-618 Lublin, Poland
e-mail: r.rusinek@pollub.pl, www.raf.pollub.pl

[†] Lublin University of Technology (LUT)
Department of Applied Mechanics, Mechanical Engineering Faculty
Nadbystrzycka 36, 20-618 Lublin, Poland
e-mail: a.weremczuk@pollub.pl, j.warminski@.pollub.pl

Key Words: *Milling, Chatter Suppression, Delay Differential Equations.*

Abstract. Harmful chatter vibrations in milling should be avoided or suppressed. Therefore dynamic aspect of milling model with vibrating workpiece are analysed in this paper. The idea, successfully implemented to orthogonal cutting, now is used for more complicated discontinuous system. The obtained results which not always give wanted response are presented as the stability lobes and bifurcation diagrams. Finally, parameters of workpiece excitation are tested to find chatter suppression zones and specific dynamic phenomena.

1 INTRODUCTION

Milling is one of the most popular method of manufacturing, therefore its productivity as well as final product quality is still an important task in engineering practice. The important problem in cutting are a self-excited chatter vibrations which, can destabilize the process. Self-excited vibrations are produced by two main mechanisms, regenerative and frictional. The former exists when flexible cutting tool or workpiece starts to vibrate due to the regeneration of the workpiece surface. A wave appearing on the workpiece causes variations in chip thickness that in turn affects variations of the cutting force and as a consequence harmful vibrations called regenerative chatter. The latter - frictional mechanism is bases on dry friction phenomenon between the tool and the workpiece and the chip and the tool. Nonlinear dry friction characteristic also leads to self-excited vibrations so called a frictional chatter.

To overcome difficulties related to chatter vibrations one can mention several methods for the elimination or suppression mainly regenerative chatter, e.g. tools with the active elimination realized by piezoelectric elements [1], a change of phase between the internal and external modulation in trace regeneration, and the change of dynamic properties of the tool – machine system put into practice through the use of dampers or dynamic eliminators [2]. A change of phase is usually performed by means of variable spindle speed or by unequal spacing of cutting flutes in the mill head in case of milling and cannot be applied to single point machining [2, 3]. The idea of the spindle speed variation (SSV) and its variation known as sinusoidal spindle speed variation (S3V) is proposed by Stöferle and Grab [4]. There are many research efforts to verify its effectiveness by numerical simulations and experiments in turning and milling. Altintas and Chan [5] designed the system of SSV in milling which may reduce vibrations on the bases of the frequency spectrum of the cutting force signal analysis and chatter detection. Kubica, Ismail [6] and also Soliman, Ismail [7] applied fuzzy logic controller which adaptively selects amplitude and frequency. Despite of research efforts, this technique has not been widely implemented in industry because there is no systematic way to obtain SSV parameters. The all above presented solutions concern linear models of cutting process. Nonlinear approach is presented in [8], where thoroughgoing stability analysis of SSV technique is shown on the ground of Hanna and Tobias model.

Above, the traditional approach to suppress vibration in a machining system is presented, but some papers offers a workholding system for the control of unwanted vibration. Such an active system which employs piezo-actuators for dynamic control of cutting force is presented in [9] The active workpiece holder is controlled by an adaptive filtering algorithm X-LMS. In consequence, the experimental system demonstrates the reduction in dynamic force due to vibration. Similar method of improving milling conditions for flexible details is proposed in [10]. The authors use the workpiece holder with adjustable stiffness variable stiffness holder in order to avoid harmful vibrations. Ma et al. propose regenerative chatter suppression in turning operations by adding the ultrasonic elliptical vibration on the cutting tool [11]. Unfortunately, this method is hardly implemented to milling operations due to difficulties to excite rotating cutter. Therefore, scientists are still looking for new concepts dedicated to milling. One of them is shown in [12] where the frictional damper is fitted into an axial hole inside the tool. In results of analytical and numerical analyses an increase of the critical cutting depth is achieved. For milling, it is possible to mount a vibration absorber on a workpiece [13] or adding the tuned mass damper to the main structure of a system [14].

In this paper, the idea of chatter control system (CCS) on the basis of harmonic excitation of a workpiece is proposed. A similar idea is presented in the paper [15] but only for orthogonal cutting. Here, the system with additional workpiece excitation is tested in case of milling operations.

2 MODEL OF MILLING

Models of milling process are non-smooth by nature because a cutting tool has several cutting blades, which are in contact with a workpiece during some time intervals of cutting. For the rest of time, tool blades are away from the workpiece. This causes discontinuities, which make difficulties in numerical simulations and analytical solutions, as well. Therefore, modelling process of milling is very important and complicated from technical point of view.

Generally, during milling a material is removed from a workpiece by a cutting tool, which rotates with speed Ω (in rpm). A schematic representation of the full immersion milling process is shown in Figure 1, as a one degree of freedom (1DOF) system.

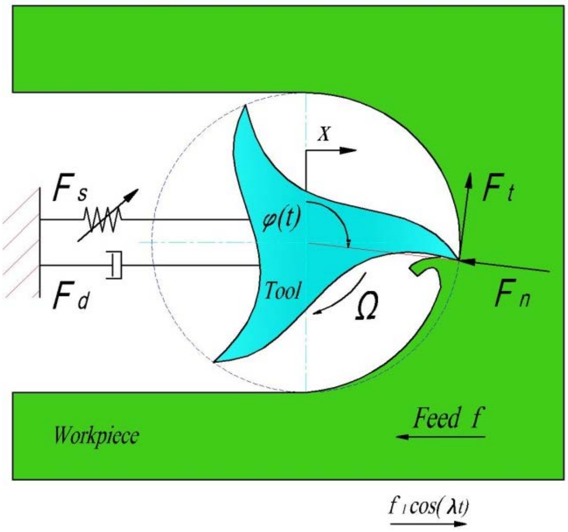


Figure 1: Modell of milling

The cutting tool is represented as a rigid body suspended on visco-elastic elements with properties defined by a viscous linear damping force (F_d) and nonlinear stiffness one (F_s).

The cutting force F_j acting on j-th tooth ($j=1,2$ .., z) in the x direction depends on an angular tool position φ_j and consists of a tangential (F_{tj}) and a normal (F_{nj}) force component (see Figure 1).

$$F_j = \left(-F_{tj}\cos\varphi_j - F_{nj}\sin\varphi_j\right) g_j, \tag{1}$$

z means the number of tool teeth, and g_j defines when j-th tooth is active. The tangential and radial cutting force acting on the tool are proportional to the axial depth of cut (a_p) and chip thickness (h_j) according to the equations

$$F_{tj} = K_t a_p h_j^{\kappa}(t),\;\; F_{nj} = K_n a_p h_j^{\kappa}(t), \tag{2}$$

K_t and K_n are specific cutting forces which depend on the cutting material properties. Typical relationship between K_t and K_n for classical materials is K_n =0.36 K_t. The coefficient κ also depends on the material, and is usually estimated from 0.75 to 1 [16-19].

The chip thickness $h_j(t)$ is a function of the feed of the cutter f, the present tool vibrations ($x(t)$) and vibrations of the previous tooth (x(t-τ), *regeneration effect*). Additionally, in order to control vibrations generated by regenerative mechanism, harmonic motion of the workpiece represented by $f\cos\lambda t$ is is added. Where, f_1 and λ mean the amplitude and frequency of the chatter control system (CCS) In practice, the CCS can be built using piezo-actuators. Theoretically, the chip thickness h_j can be positive or negative, but only positive value has a practital meaning. Therefore, the actual chip thickness h_j is defined with the help of Heaviside step function H() as follows

$$h_j = \left[f + x(t) - x(t-\tau) - f_1\cos(\lambda t)\right]\sin\varphi_j H(h_j) \tag{3}$$

Where, $\tau=60/z\Omega$ is the tooth passing period, Ω means rotational speed of the tool.

The key meaning, for the sake of numerical simulations, has the step function g_j , which defines whether the tool is in cut or not:

$$g_j\left(\varphi_j\right)=\left\{\begin{matrix} 1, & \varphi_s \le \varphi_j \le \varphi_e \ and \ h_j>0 \\ 0 & elsewhere \end{matrix}\right\}. \tag{4}$$

Usually, the conditions described in Eq. (4) are realized by non-smooth Heaviside function H() but sometimes it is better to change H() by another smooth function. In order to calculate the total milling forces, the number of teeth (*z*) of the cutter, the radial depth of cut *(a_e)* and diameter of cutter *(d)* must also be known. Then, the entry *(φ_s)* and exit *(φ_e)* angles are defined as follows

$$\varphi_s=\arcsin\left(\frac{d-2a_e}{d}\right), \quad \varphi_e=\pi/2. \tag{5}$$

In analysing here case of full immersion milling, according to Figure 1 and equation (5)

$$\varphi_s=0, \quad \varphi_e=\pi/2 \tag{6}$$

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

$$m\ddot{x}+F_d+F_s=a_p\sum_{j=1}^{z}h_j(t)^{\kappa}\left(-K_t\cos\varphi_j-K_n\sin\varphi_j\right)g_jH(h_j), \tag{7}$$

Where, *m* is mass of the tool. The stiffness (F_s) and damping force (F_d) are defined

$$\begin{aligned} F_d &= c\dot{x} \\ F_s &= kx+\gamma x^3 \end{aligned} \tag{8}$$

c means the viscous damping coefficient, *k* and γ are linear and nonlinear stiffness coefficient respectively. These parameters in numerical analysis are obtained from [20]. Finally, the equation of motion takes the form

$$\ddot{x}+2\xi\omega_n\dot{x}+\omega_n^2x+\frac{\gamma}{m}x^3=\frac{a_p}{m}\sum_{j=1}^{z}h_j(t)^{\kappa}\left(-K_t\cos\varphi_j-K_n\sin\varphi_j\right)g_jH(h_j) \tag{9}$$

As mentioned above, for ease of numerical computations the discontinuous Heaviside function H() is replaced by its smooth approximation using the sigmoid function given by

$$H(x)=\frac{1}{1+e^{-\sigma x}}, \tag{10}$$

For different values of σ the curve defined by eq. (10) can be smooth (see Figure 2) and similar to the original Heaviside drawn as solid line.

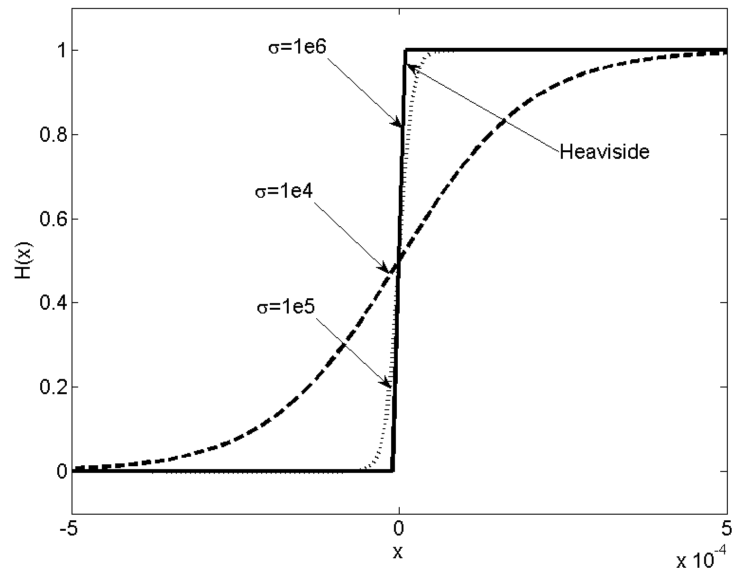


Figure 2: Heaviside function and its smotthed approximation

In our computation we assume $\sigma = 1e6$. The above substitution does not have any significant effect on the system dynamics. However, the results are obtained almost 10 times faster with the smoother version using the MATLAB inbuilt command *ode45* with a specified tolerance of *1e-6* for numerical integration.

3 CHATTER VIBRATIONS

On the basis of nonlinear, discontinuous one degree of freedom model presented in the previous section chatter vibrations are analyzed numerically in Matlab. Parameters for numerical analysis are as follows: f=0.01mm, ω_n=6324.55rad/s, m=0.02kg, ξ=0.01, γ=2e12N/m^3 and initial conditions x_o=0.01mm, v_o=0.

From practical point of view stability lobes diagrams (SLD) are important because they tell us where chatter vibrations exist and enable to choose proper spindle speed (n) and depth of cut (a_p). It is obvious that in unstable lobes (colour regions in Figure 3) system (tool) vibrates, but a kind of vibrations depends among other on κ parameter. Colour on the SLD (Figure 3) represents amplitude of vibrations. Moreover, Figure 3 and Figure 4 show an influence of a number of teeth and exponent κ. Increasing teeth quantity of the tool the unstable lobes are lower that means the critical depth of cut is smaller. Enlarging nolinearity of the system by decreasing κ the unstable region is enhanced regardless teeth number.

In case of κ=1, milling with the help of one tooth tool is more beneficially because stable regions are significantly bigger (the critical depth of cut is much higher). This advantage disappear when κ=0.75 (Figure 3 and Figure 4). Moreover in case of z=1, vibrations amplitude is bigger especially for high spindle speed and depth of cut (in the right upper corner). An influence of exponent κ is examined on the bifurcation diagrams (Figure 5). Interestingly, the regular vibrations (represented by the simple line) undergo into chaotic ones when decreasing exponent κ from 1 (linear case for the sake of cutting force) to 0.75. Chaotic vibrations appears only when the depth of cut (a_p) is big enought. For a_p =0.2mm chaos is not observed in the system.

a)

b)

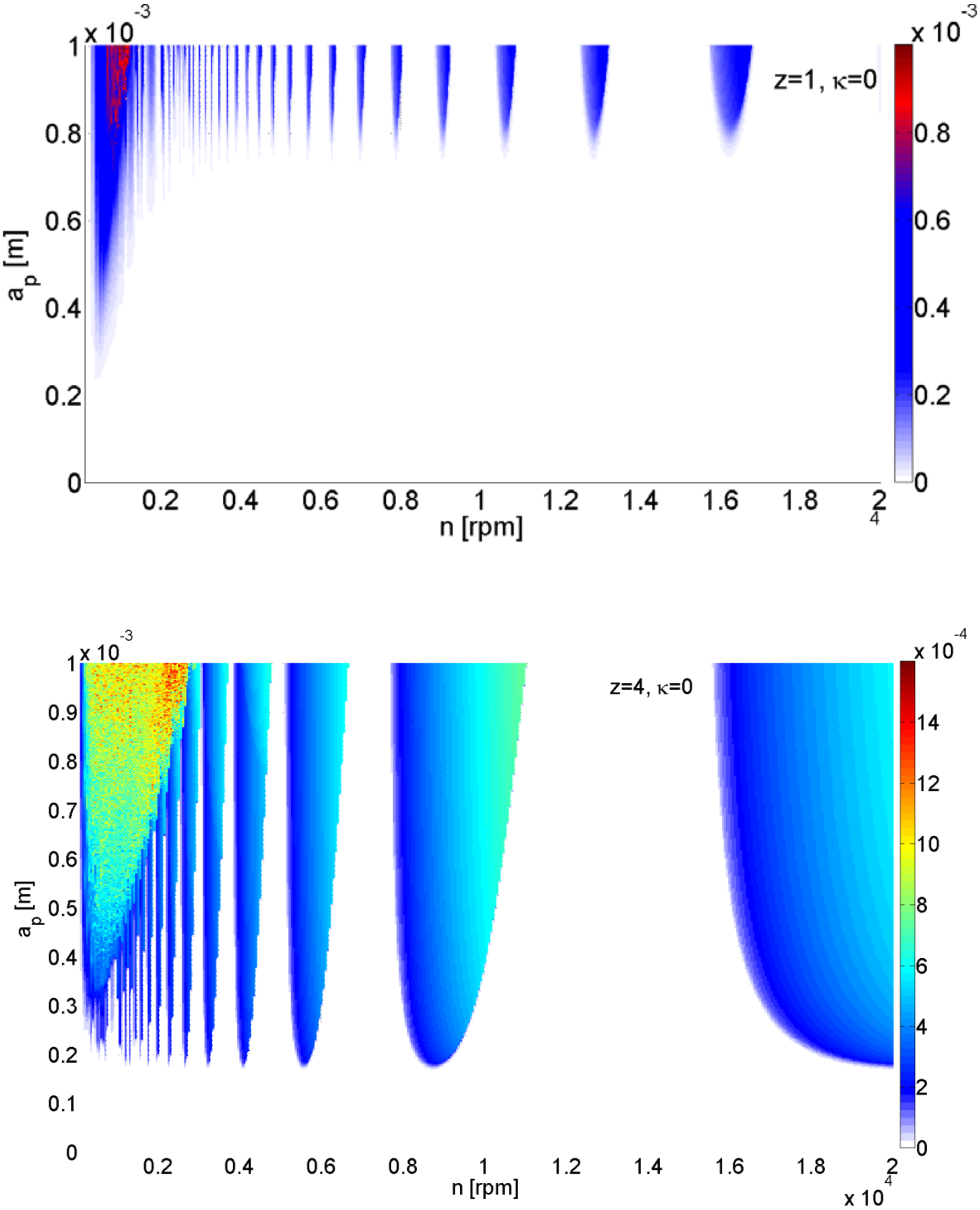


Figure 3: Stability lobes diagrams for κ=1, a) z=1, b) z=4

a)

b)

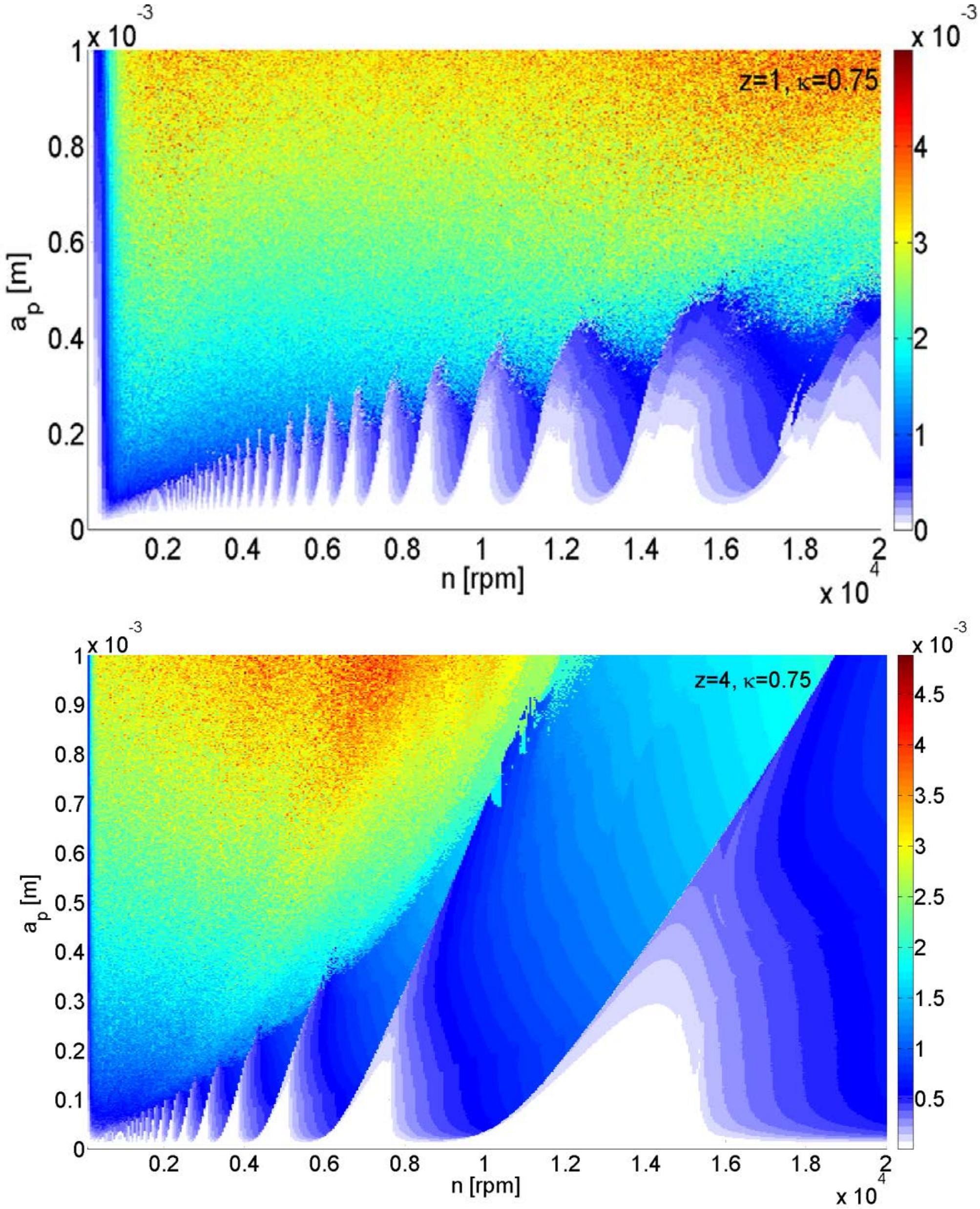


Figure 4: Stability lobes diagrams for κ=0.75, a) z=1, b) z=4

Since the system generates self-excited vibrations which are not commensurable to the natural frequency, therefore even the harmonic response does not give one point on a classical Poincaré map and bifurcation diagram, but the close loop. Therefore, the presented diagrams (Figure 5) collect the point where velocity equals zero. Thus, they do not give any information about periodicity.

a) b)

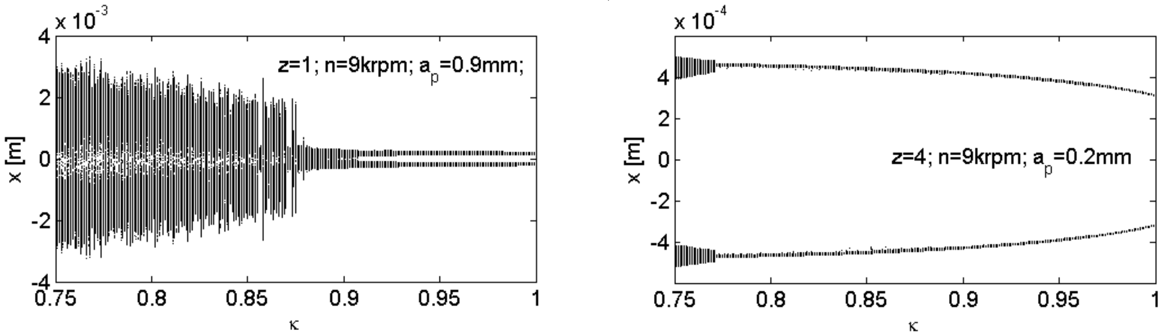


Figure 5: Bifurcation diagrams versus exponent κ; a) z=1 n=9krpm, a_p=0.9; b) z=4 n=9krpm, a_p=0.2

a) b)

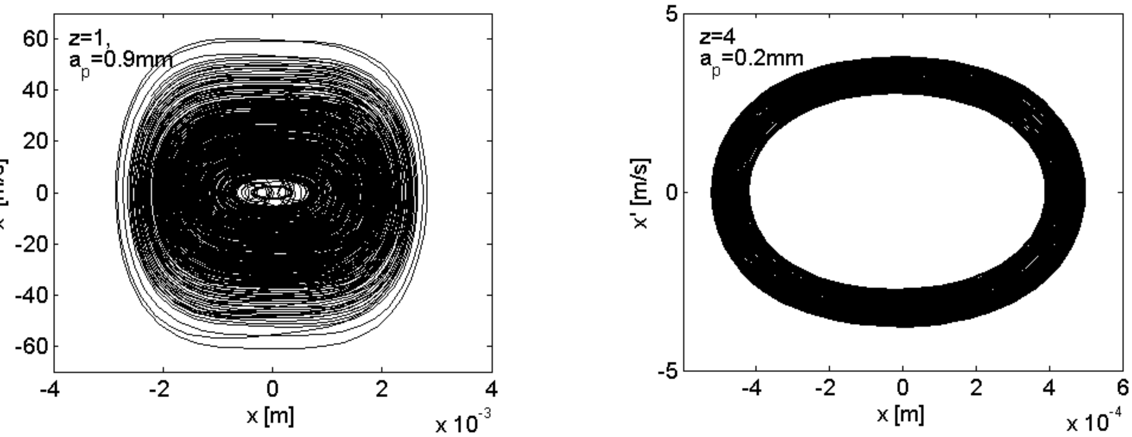


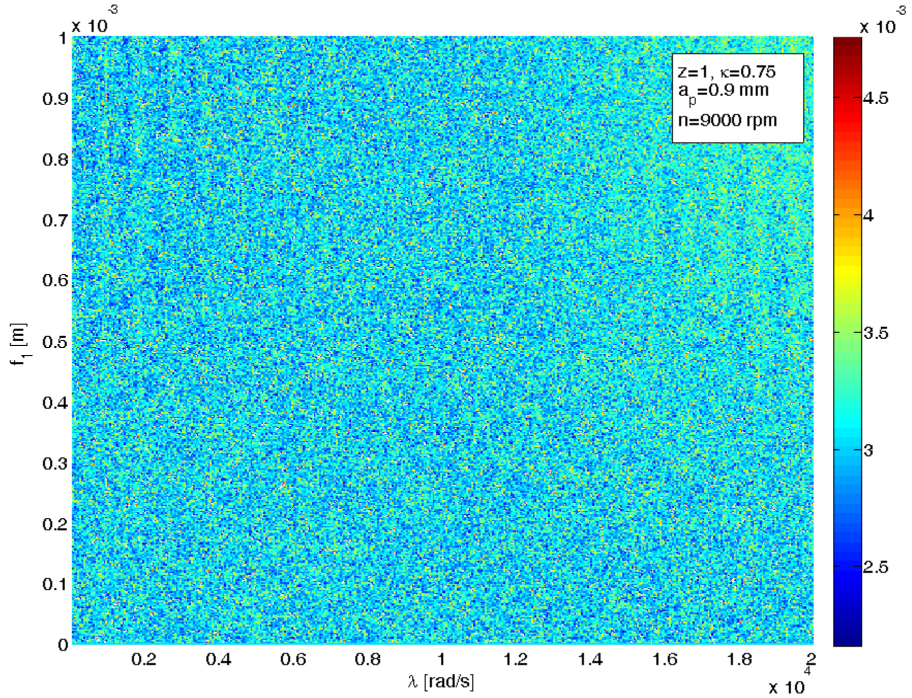
Figure 6: Phase space for chaotic (a) and regular (b) motion

The symmetric chart in bifurcation diagrams arises because the attractor crosses zero velocity two times on a phase plane. As an example the phase space for chaotic and regular motions are presented in Figure 6 respectively.

3.1 Chatter control

The idea of chatter control is applied here for milling process. Milling which is discontinuous operation by nature. A set of control parameters, that is workpiece excitation amplitude f_1 and frequency λ, is tested here in order to find such which can decrease chatter amplitude. The results are presented in Figure 7 as a colour map where colour depicts the vibrations amplitude. Unfortunately, the assumed results are not achieved for z=1 and a_p=0.9mm in the analysed range of parameters (Figure 7a). Introducing extra workpiece excitation is not able to improve cutting conditions. Vibrations amplitude of the system with CCS is always bigger comparing the system without SSC.

a)



b)

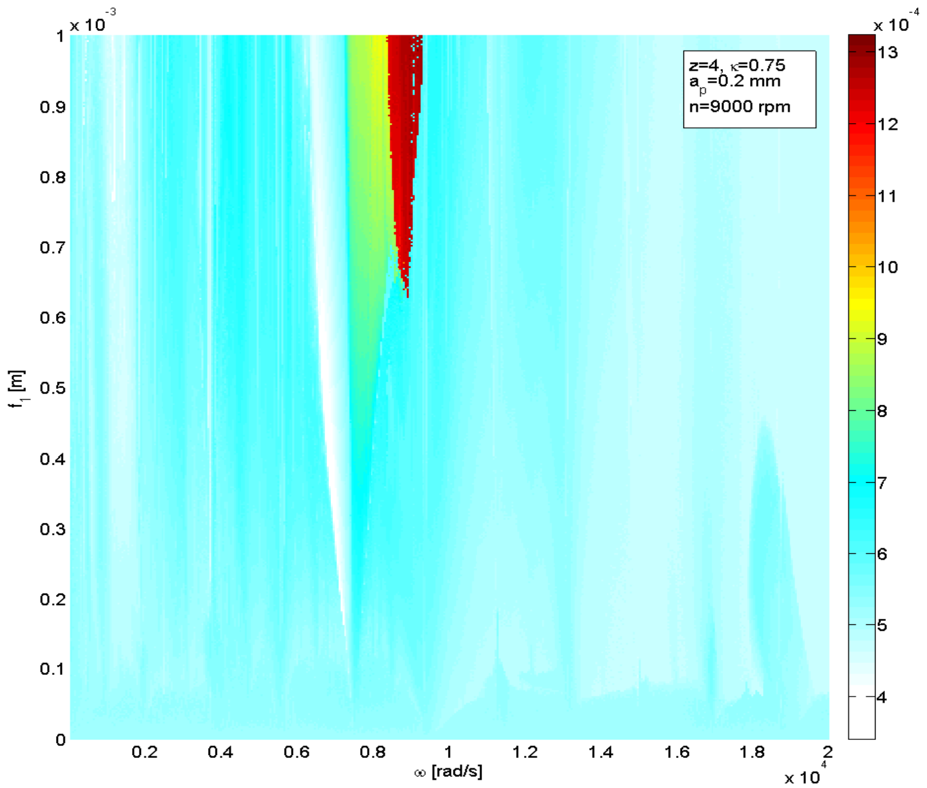


Figure 7: Vbrations amplitude as a colour map (in meters) versus workpiece excitation amplitude f_1 and frequency λ, z=1, a_p=0.9mm (a), z=4, , a_p=0.2mm (b)

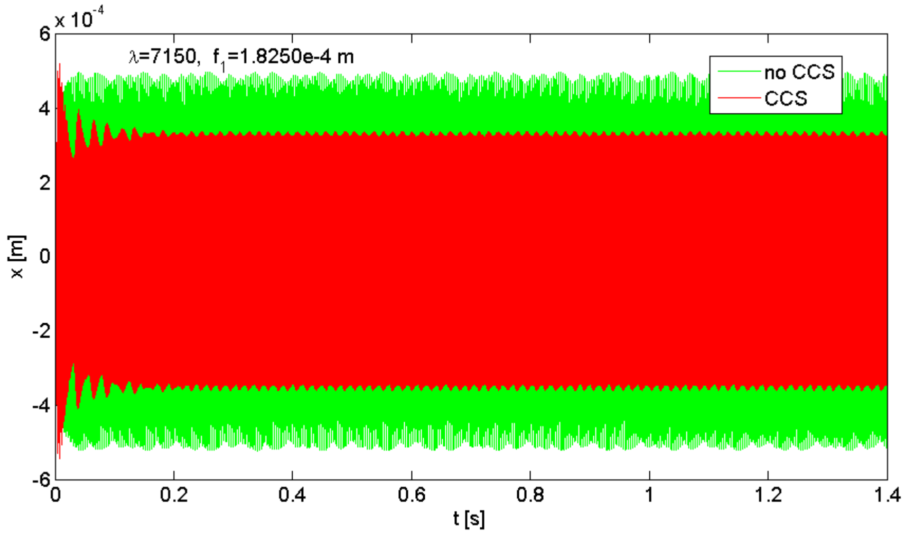


Figure 8: Time series of vibrations in case of activated and deactivated CCS for λ=7150rad/s and f_1=0.1825mm

That is probably caused by discontinuity effect which is present in milling operations. Similar system works correctly in case of turning operations because turning is continuous process. However, for 4 blades (z=4) and smaller depth of cut a_p=0.2mm it is possible to find the proper excitation parameters in order to decrease chatter vibrations (Figure 7b). The exemplary time series for the milling system with and without CCS is presented in Figure 8, where the excitation parameters taken from Figure 7b are λ=7150rad/s and f_1=0.1825mm. A decrease of the chatter amplitude is about 30%. This results can be improved providing a close loop control will be applied in the CCS. Now, the CCS system works only in open loop, but the possibility of chatter suppression is acknowledge.

12 CONCLUSIONS

Chatter control system, proposed in this paper, is applied for milling process in order to suppress chatter vibrations. This idea was successfully introduced for some specific turning and milling operations. Here the model of milling process is nonlinear and discontinuous, that complicate its dynamics. Especially, the exponent κ different from 1 causes chatter vibrations for small depth of cut which normally does not generate chatter. That all have an influence of CCS which does not always fulfill our expectations concerning chatter suppression. It is probably, that better results can be found for modyfied modell of milling with chatter control system which works in close loop control or for wider range of parameters. This kind of research is still in progress.

ACKNOWLEDGMENTS

The work is financially supported under the project of National Science Centre according to decision no. DEC-2011/01/B/ST8/07504. The second author is financially supported by

Structural Funds in the Operational Programme - Innovative Economy (IE OP) financed from the European Regional Development Fund - Project "Modern material technologies in aerospace industry", Nr POIG.01.01.02-00-015/08-00.

REFERENCES

[1] Neugebauer, R., Denkena, B., and Wegener, K., Mechatronic Systems for Machine Tools. *CIRP Annals - Manufacturing Technology* (2007) 56:657-686.

[2] Parus, A., Pajor, M., and Hoffmann, M., Suppression of Self-Excited Vibration in Cutting Process Using Piezoelectric and Electromagnetic Actuators. *Advances in Manufacturing Science and Technology* (2009) 33:35-50.

[3] Al-Regib, E. and Ni, J., Chatter Detection in Machining Using Nonlinear Energy Operator. *Journal of Dynamic Systems, Measurement, and Control* (2010) 132:034502.

[4] Jemielniak, K. And Widota, A., Suppression Of Self-Excited Vibration By The Spindle Speed Variation Method. *International Journal of Machine Tools & Manufacture* (1984) 24:207-214.

[5] Altintas, Y. and Chan, P. K., In-Process Detection And Suppression Of Chatter In Milling. *International Journal of Machine Tools & Manufacture* (1992) 32:329-347.

[6] Kubica, E. G. and Ismail, F., Active suppression of chatter in peripheral milling. Part II. Application of fuzzy control. *The International Journal of Advanced Manufacturing Technology* (1996) 12:236-245.

[7] Soliman, E. and Ismail, F., Chatter suppression by adaptive speed modulation. *International Journal of Machine Tools & Manufacture* (1997) 37:355-369.

[8] Namachchivaya, N. S. and Beddini, R., Spindle Speed Variation for the Suppression of Regenerative Chatter. *Journal of Nonlinear Science* (2003) 13:265-288.

[9] Rashid, A. and Mihai Nicolescu, C., Active vibration control in palletised workholding system for milling. *International Journal of Machine Tools and Manufacture* (2006) 46:1626-1636.

[10] Kalinski, K. J., Chodnicki, M., Mazur, M. R., and Galewski, M. A., "Vibration surveillance system with variable stiffness holder for milling flexible details," *12-th Conference on Dynamical Systems Theory and Applications*, Lodz 2013.

[11] Ma, C., Ma, J., Shamoto, E., and Moriwaki, T., Analysis of regenerative chatter suppression with adding the ultrasonic elliptical vibration on the cutting tool. *Precision Engineering-Journal of the International Societies for Precision Engineering and Nanotechnology* (2011) 35:329-338.

[12] Madoliat, R., Hayati, S., and Ghalebahman, A. G., Investigation of chatter suppression in slender endmill via a frictional damper. *Scientia Iranica* (2011) 18:1069-1077.

[13] Sims, N. D., Vibration absorbers for chatter suppression: A new analytical tuning methodology. *Journal of Sound and Vibration* (2007) 301:592-607.

[14] Wang, M., Feasibility study of nonlinear tuned mass damper for machining chatter suppression. *Journal of Sound and Vibration* (2011) 330:1917-1930.

[15] Yao, Z., Mei, D., and Chen, Z., Chatter suppression by parametric excitation: Model and

experiments. *Journal of Sound and Vibration* (2011) 330:2995-3005.
[16] Insperger, T., Stepan, G., Bayly, P. V., and Mann, B. P., Multiple chatter frequencies in milling processes. *Journal of Sound and Vibration* (2003) 262:333-345.
[17] Insperger, T., Mann, B. P., Stepan, G., and Bayly, P. V., Stability of up-milling and down-milling, part 1: alternative analytical methods. *International Journal of Machine Tools and Manufacture* (2003) 43:25-34.
[18] Kecik, K., Rusinek, R., Warminski, J., and Weremczuk, A., Chatter control in the milling process of composite materials. *Journal of Physics: Conference Series* (2012) 382:012012.
[19] Szalai R., Stepan G., and Hogan S.J., Global dynamics of low immersion high-speed milling. *Chaos* (2004) 14:1069-1077.
[20] Young, S. M., Dynamics of Low Immersion Milling. (2008) PhD thesis, University of Maryland.