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NUMERICAL SIMULATION OF SELF-EXCITED VIBRATIONS UNDER VARIABLE CUTTING CONDITIONS

A self-excited vibrations are one of the most important constraints to the performance and quality of machining part and it is affecting its dimensions and geometrical accuracy. Machining stability can be evaluated by different analytical and numerical methods. The paper presents utilization of numerical simulation of non-linear chatter in the time domain in stability analysis of machining process. Vibrations and cutting forces are an output from numerical simulation. In order to perform chatter recognition during excessive vibrations an automatic chatter detection is implemented in machining simulation. By combining all the above in one and enabling G-code reading, a tool for numerical simulation and validation of entire machining operation was created which is a subject of this paper.

1. INTRODUCTION

Self-excited vibrations occurring in the cutting process are a major limitation for the achievable performance, machining quality, tools life and durability of machine tools. There is a need of stability limit estimation enabling selection of cutting parameters which suppress self-excited vibrations. The machine-tool-workpiece system is a structure with many degrees of freedom, in most applications, such as turning and milling, it can be reduced to a multimodal system with two degrees of freedom [1],[2]. It still takes under consideration two main sources of self-excited vibrations in machining, which are mode coupling and regenerative effect.

2. FUNDAMENTALS OF NUMERICAL SIMULATION OF SELF-EXCITED VIBRATION IN MILLING

The variable cutting force components F_r and F_t (see Fig. 1.) depend on dynamic changes of the uncut chip thickness caused by relative displacement between the workpiece

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and the tool in radial direction (inner modulation of the uncut chip thickness r_t) and the machined surface waviness left during the previous pass (outer modulation r_T) and the velocity of these displacements (r_t'). Influence of vibration in tangential direction t is generally ignored. Forces F_r and F_t projected to the x, y directions give F_x and F_y froces causing vibration of the machine-tool system. Stability analysis is usually based on analytical or numerical solution of differential equations of the system motion in the frequency domain [3],[8]. Despite the convenience of stability limit calculation the main disadvantage of these methods is the inability (or very high difficulty) to consider machine-tool system characteristic and cutting parameter changes in a space and time. These limitations stimulate attempts of stability analysis based on time domain numerical simulation by many research centers [9],[10].

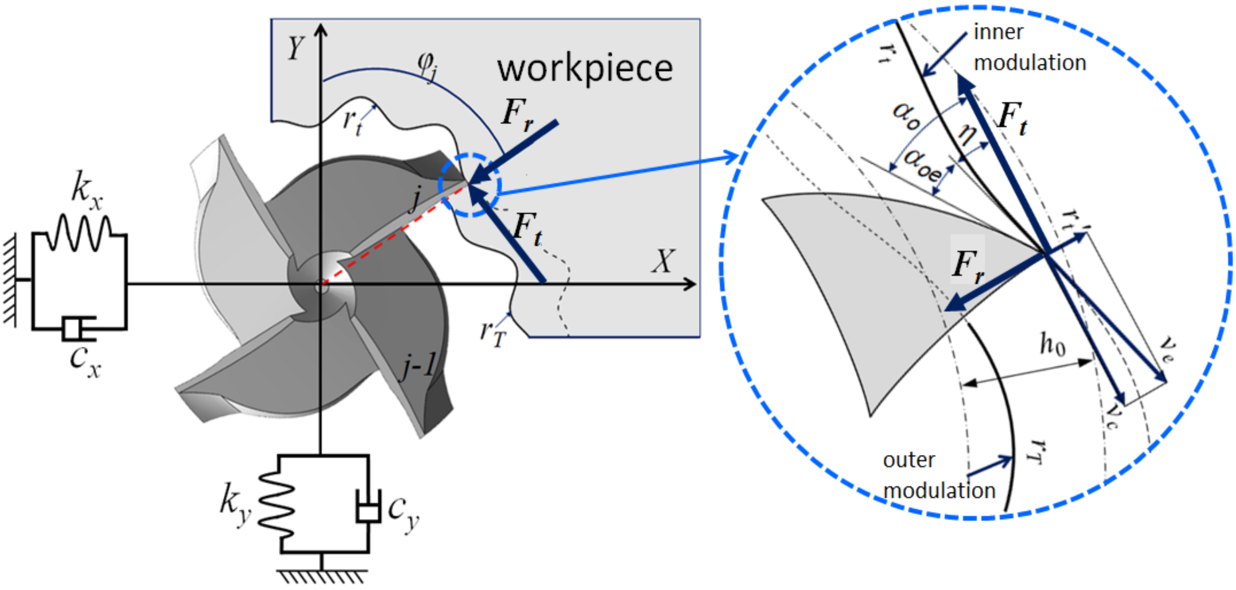


Fig. 1. 2D Dynamic system in milling process [5]

In a single iteration of a typical algorithm of numerical simulation the following steps can be identified as follows [5]: calculation of the current displacement (x_i, y_i) and velocity (x_i', y_i') for the each vibration mode i separately:

$$p" = \left(F_{pB} - c_p\, p_B' - k_p\, p_B\right)/m_p \tag{1}$$

$$p' = p_B' + p"\mathrm{d}t \tag{2}$$

$$p = p_B + p'\mathrm{d}t \tag{3}$$

where $p = x$ or y, index B – forces, displacement and velocities in the previous iteration – and subsequently summed up.

Then displacements and velocities of the system (*x*, *y*) are projected to the *r* direction using convertion matrix **B**, individually for each segment of the cutting edge. Displacements *r* are stored as an outer modulation r_T and used in the next tool pass. Variable force components F_r and F_t are determined in the cutting process coordinates (*r*, *t*) on the base of the selected model dependences of these forces on r_t , r_t' and r_T. Finally of the F_r and F_t forces are projected to the F_x and F_y forces using convertion matrix **A** and summing them up along the cutting edge (Fig. 2).

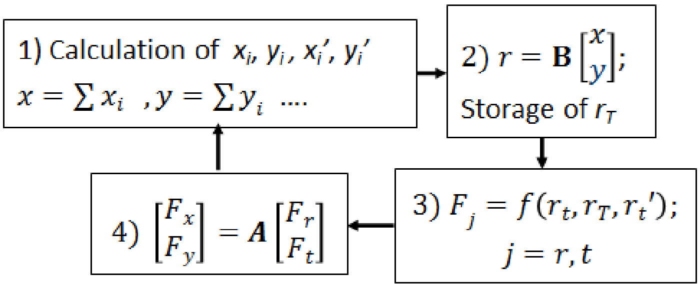
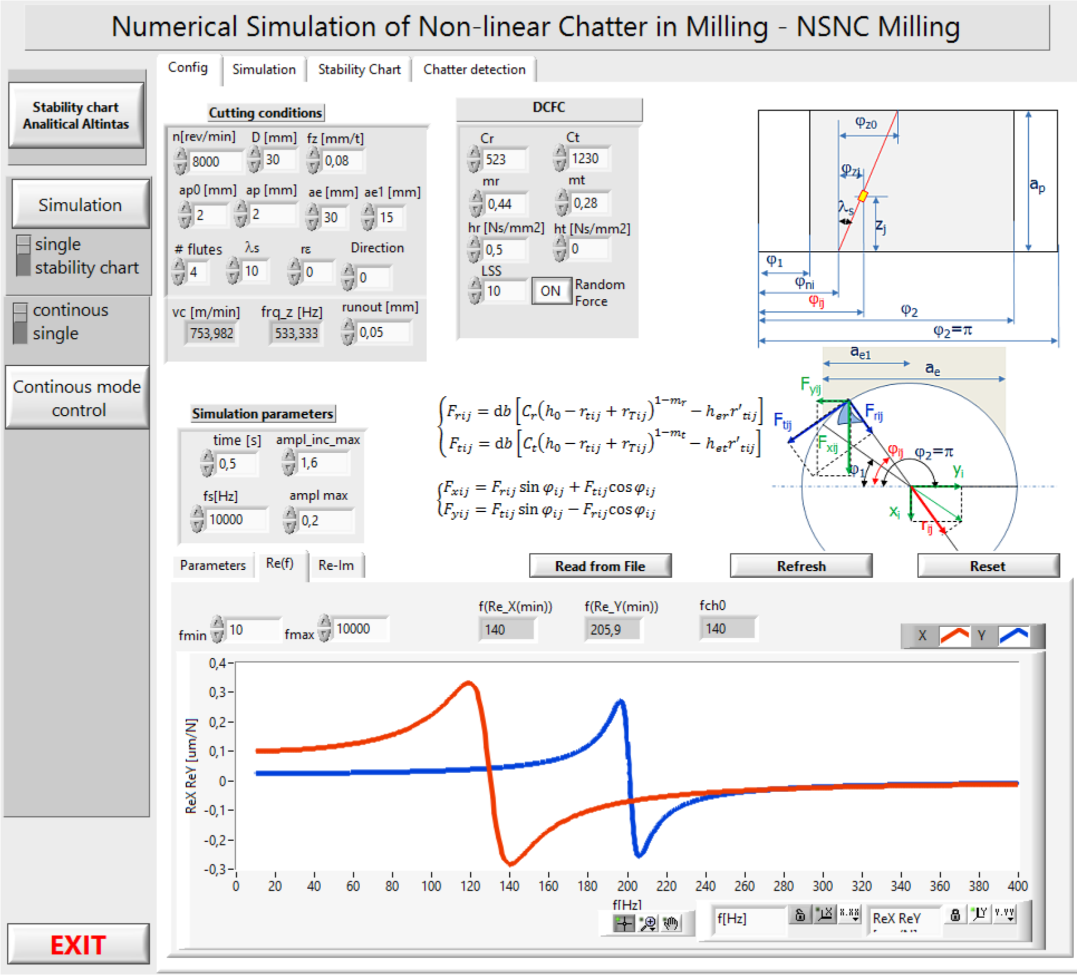


Fig. 2. A single iteration algorithm of numerical simulation of self-excited vibrations [5]


Numerical Simulation of Non-linear Chatter in Milling - NSNC Milling

Cutting conditions
n[rev/min] 8000
D [mm] 30
fz [mm/t] 0,08
ap0 [mm] 2
ap [mm] 2
ae [mm] 30
ae1 [mm] 15
flutes 4
λs 10
rε 0
Direction 0
vc [m/min] 753,982
frq_z [Hz] 533,333
runout [mm] 0,05

DCFC
Cr 523
Ct 1230
mr 0,44
mt 0,28
hr [Ns/mm2] 0,5
ht [Ns/mm2] 0
LSS 10
ON Random Force

Simulation parameters
time [s] 0,5
ampl_inc_max 1,6
fs[Hz] 10000
ampl max 0,2

$$\begin{cases} F_{rij} = \mathrm{d}b\left[C_r\left(h_0 - r_{tij} + r_{Tij}\right)^{1-m_r} - h_{er}r'_{tij}\right] \\ F_{tij} = \mathrm{d}b\left[C_t\left(h_0 - r_{tij} + r_{Tij}\right)^{1-m_t} - h_{et}r'_{tij}\right] \end{cases}$$

$$\begin{cases} F_{xij} = F_{rij}\sin\varphi_{ij} + F_{tij}\cos\varphi_{ij} \\ F_{yij} = F_{tij}\sin\varphi_{ij} - F_{rij}\cos\varphi_{ij} \end{cases}$$

fmin 10
fmax 10000
f(Re_X(min)) 140
f(Re_Y(min)) 205,9
fch0 140

Fig. 3. Front panel of the NSNC Milling program

Here the following model of the cutting force was aplied:

$$F_r = b[C_r(h_0 - r_t + r_T)^{1-m_r} - h_{er}r'_t] \quad (4)$$

$$F_t = b[C_t(h_0 - r_t + r_T)^{1-m_r} - h_{er}r'_t] \quad (5)$$

Using this approach a software for numerical simulation of non-linear chatter in milling (NSNC Milling) has been developed. Front panel of the program is presented in Fig. 3.

As input it requires specifying cutting conditions and simulation parameters, dynamic cutting force coefficient and modal parameters [7],[8].

In this paper the following values were applied as the initial ones in all simulations: Modal parameters on the X axis modal mass m_x =15kg, modal damping c_x =2Ns/mm, modal stiffness k_x =10kN/mm. On the Y axis modal mass m_y = 25kg, modal damping c_y =1.5 Ns/mm, modal stiffness k_y =40kN/mm.

Dynamic cutting force coeficcients: C_r = 523N/mm^2; C_t = 1230N/mm^2; m_r = 0.44; m_t = 0.28; h_r = 0.5Ns/mm^2. Simulation settings: time: variable, sampling frequency: 10kHz. Cutting conditions: tool diameter 10mm, radial depth of cut: full slot, number of flutes 2, helix angle 10 degree and nose radius 0.5mm.

3. METHOD OF SIMULATED SELF-EXCITED VIBRATION DETECTION

Crucial for the stability analysis of self-excited vibration is its detecting on-line, during cutting or simulation. Displacement signal during stable milling contains only forced vibration in tooth passing frequency. Due to the fact that the forced vibration amplitude can be significant a threshold value limit of this amplitude cannot be used as stability indicator [4].

A method self-excited vibration detection used in this paper is based on the FFT spectrum in which tooth passing frequency and the rotational speed (rps) of the spindle are filtered out. Therefore, it is crucial to detect the exact actual spindle speed, as it can differ from the nominal, preset speed. The difference would contribute significantly to the outcome of the analysis. The proposed algorithm detects the actual speed. For this purpose, the nominal spindle rotational frequency is calculated:

$$f_{SP0} = n_0/60\ Hz \quad (6)$$

where:n_0 (rpm)– preset rotational spindle speed

Then, in the range of 90% -110% of the nominal rotational frequency f_0 a maximum is detected in the FFT spectrum, and is assumed to be the actual spindle rotational speed in (rps) f_{SP}. Thus tooth passing frequency and its harmonic detection can be described as:

$$f_{tpi} = N\ f_{SP}\ z \quad (7)$$

where: N - successive natural numbers starting from 1, z - number of teeth.

These frequencies, together with rotational frequency f_{SP} must be excluded from the FFT spectra during chatter detection procedure. Figure 4 presents cutter vibrations during 0.5 second of stable machining with rotational spindle speed n = 3000rpm, feed on tooth 0.08mm/t, number of teeth z = 2, diameter D = 10mm. Figure 5 left shows the FFT spectrum, in which f_{SP} and f_{itp} were marked with red points, while on the right side there is the same spectrum with these frequencies eliminated.

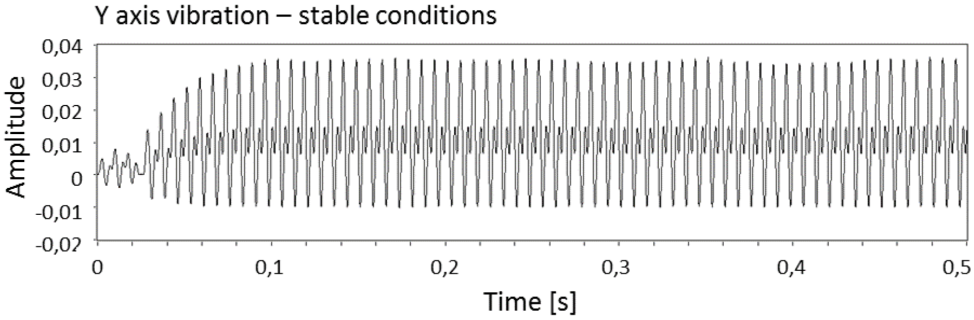


Fig. 4. Milling simulation results – stable conditions

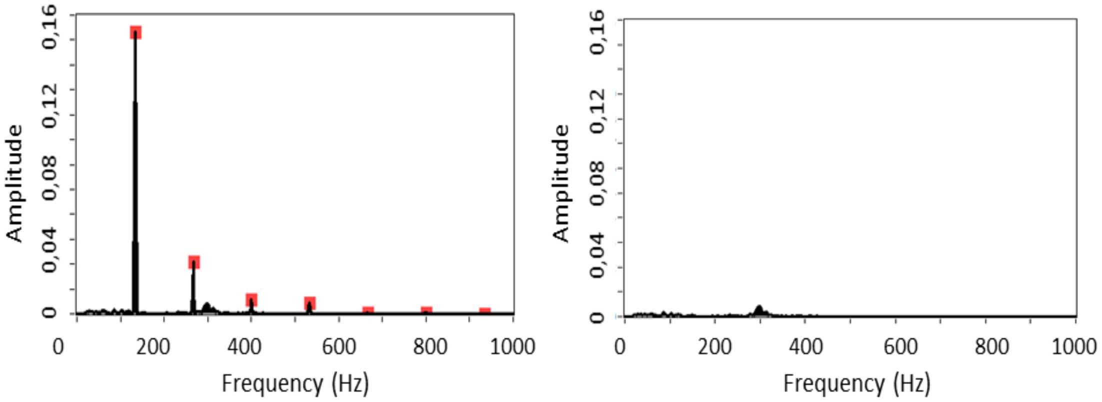


Fig. 5. Chatter detection in stable conditions – left original spectrum, right spectrum with recognized frequencies removed

The next example, for unstable conditions is shown in Fig. 6 and 7 were much higher vibration amplitude can be seen. Moreover elimination of f_{SP} and f_{itp} revealed frequencies of chatter. Then the maximum peak in initial spectrum and spectrum with recognized frequencies removed are compared. If the maximum amplitude in resultant spectrum is lower than in initial spectrum it is indicated as chatter condition.

4. MANUAL CUTTING PARAMETERS MODIFICATION DURING SIMULATION

By manual modification of the cutting parameters during the simulation, it is possible to control the virtual machine. The simulation starts with the initial parameters. The modification of parameters is made by using the controls on the front panel of the program.

In the case of manual control, it is possible to manipulate the following parameters: axial depth of cut, spindle rotational speed, direction of feed, feed rate, radial depth of cut a_e and a_{e1}, tool diameter, and tool geometry. In order to enable feed in any direction a mechanism of the temporary rotating coordination system was introduced, see Figure 8.

$$r = x\cos(\varphi + \alpha) + y\sin(\varphi + \alpha) \tag{8}$$

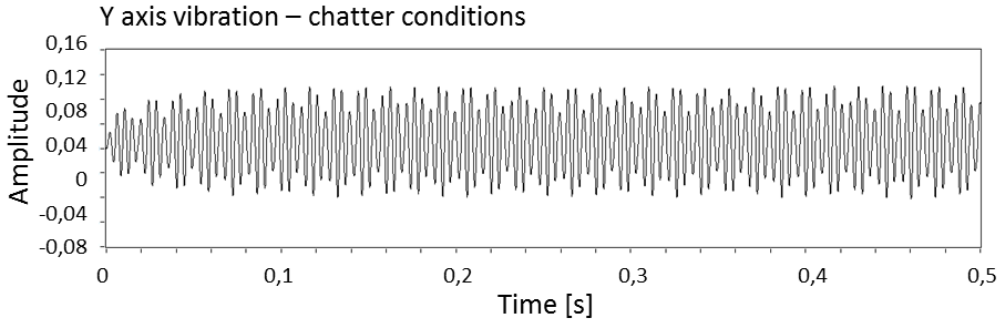


Fig. 6. Milling simulation results – chatter

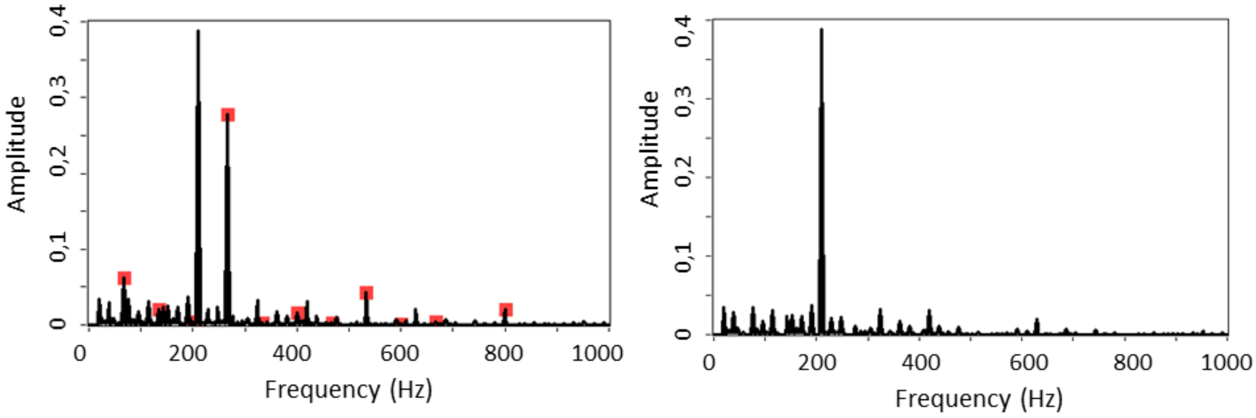


Fig. 7. Chatter detection in unstable conditions – left original spectrum, right spectrum with recognized frequencies removed

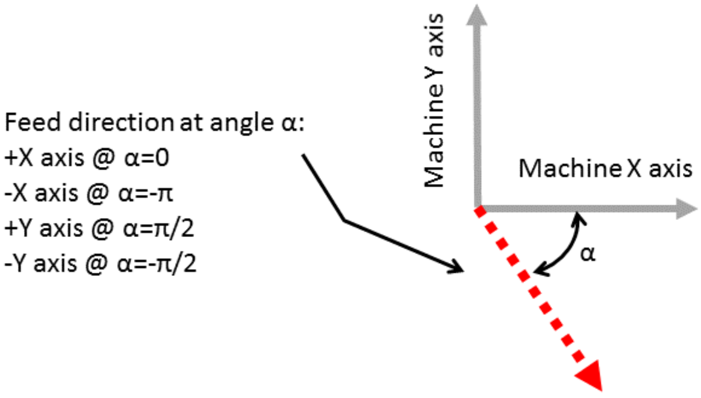


Fig. 8. Feed direction in function of direction angle α

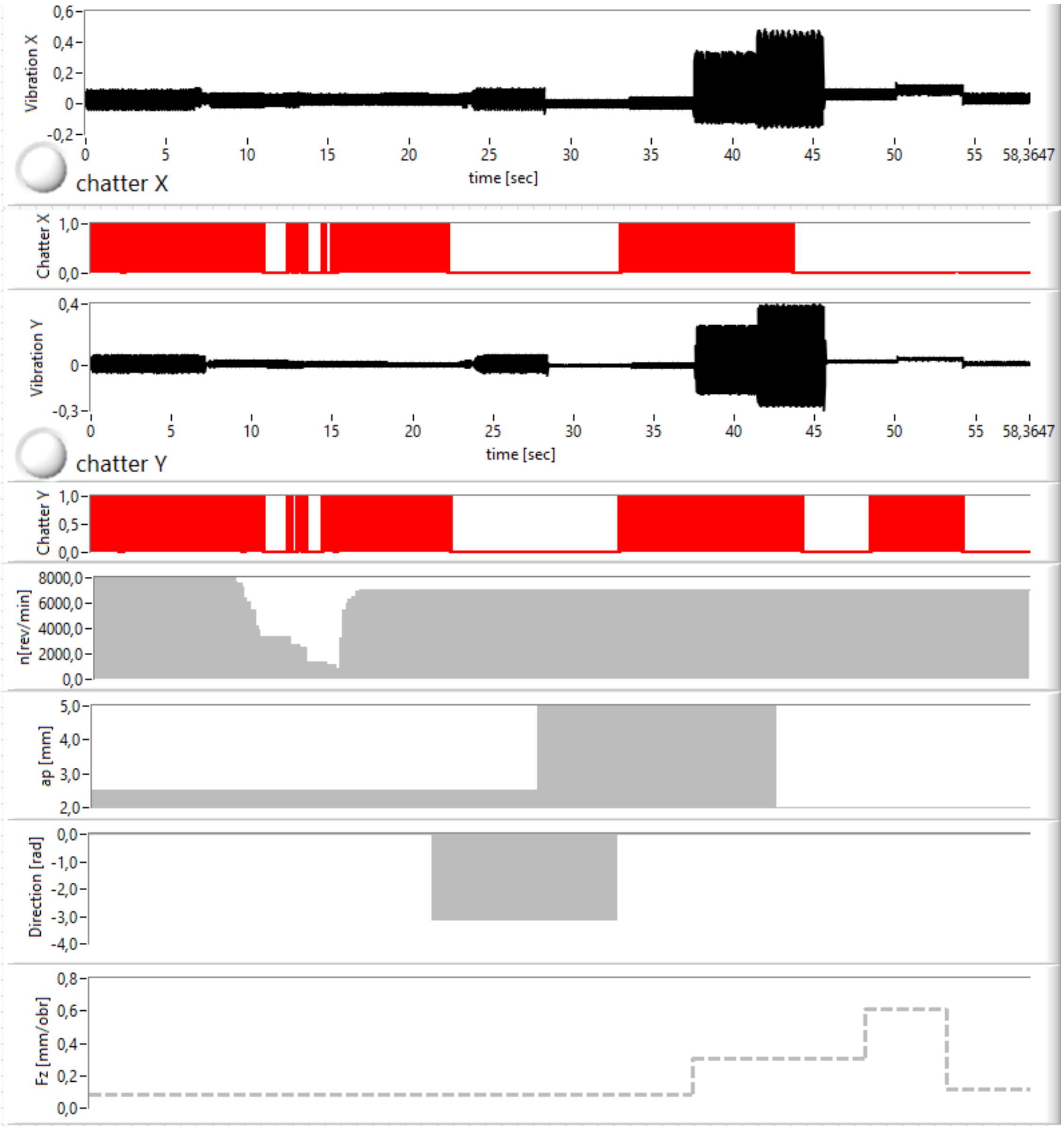


Fig. 9. Vibrations on X and Y axis under variable cutting parameters in manual mode

The preview window of the current results of numerical simulation allows for observation of the influence of applied simulation parameter changes on machining process –see Fig. 9. The chatter is detected on the both axes independently.

5. IMPLEMENTATION OF MACHINE CODE HANDLING IN NUMERICAL SIMULATION SOFTWARE

The introduction of the machine code handling allows for using the programs prepared for the CNC machines from actual production and simulation of the vibrations and forces during the production process. This enables virtual verification of the CNC programs.

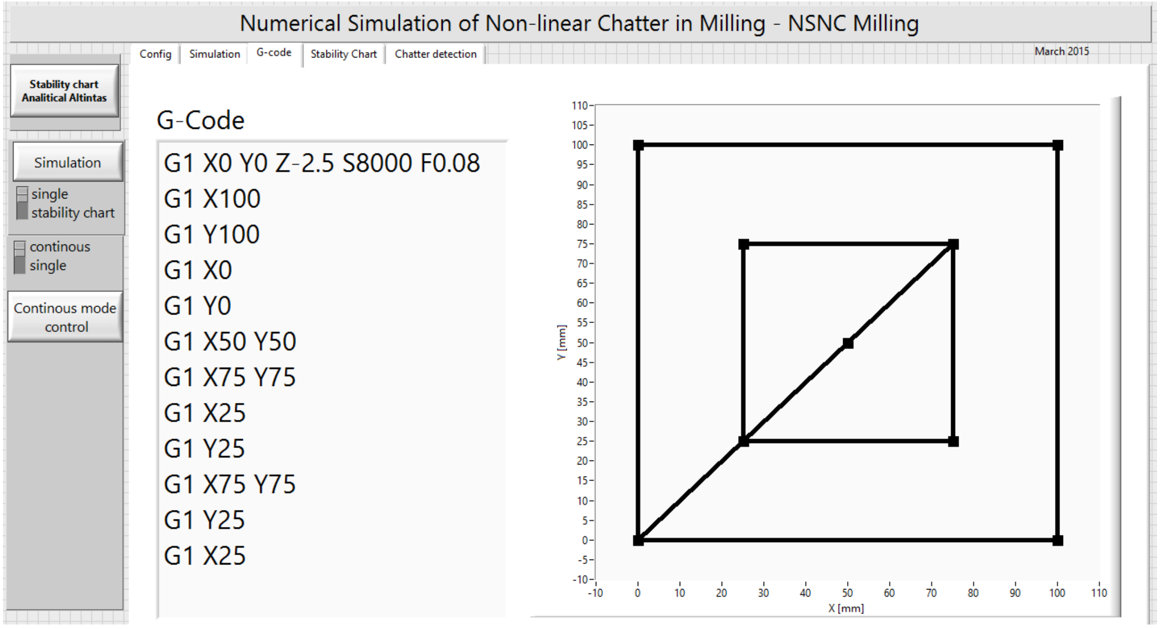
5.1. INTRODUCTION OF THE MACHINE CODE

Machine codes, also known as G or ISO codes are used for programming Computer Numerical Controlled Machines. These codes contain a variety of information regarding the movements of the machine axes, determine the speed of the feed and rotational speed.

At the current stage of software development only codes of linear interpolation (G1) with selected feed per tooth rotational speed are supported. The single line of the code defines coordinated linear motion to the destination point, e.g. G1 X12.43 Y23.23 Z-0.5 S2000 F0.25 means “linear move to the point X=12.43, Y=23.23, Z=-0.5 with rotational speed 2000rmp and feed 0.25mm/tooth. If any of the parameters do not change, are the same like in the previous line, they might be omitted.

5.2. NUMERIC SIMULATION WITH THE USE OF MACHINE CODE

As an example of numerical simulation of machining stability during, a simple CNC program was introduced to the NSNC milling program, visible in Fig. 10 together with the tool trajectory.



```
G1 X0 Y0 Z-2.5 S8000 F0.08
G1 X100
G1 Y100
G1 X0
G1 Y0
G1 X50 Y50
G1 X75 Y75
G1 X25
G1 Y25
G1 X75 Y75
G1 Y25
G1 X25
```

Fig. 10. CNC code handling window

Simulation time corresponds to the machining time calculated from the CNC program. Like in manual cutting parameters modification a separate window allows to see the results of the simulation – see Fig. 11.

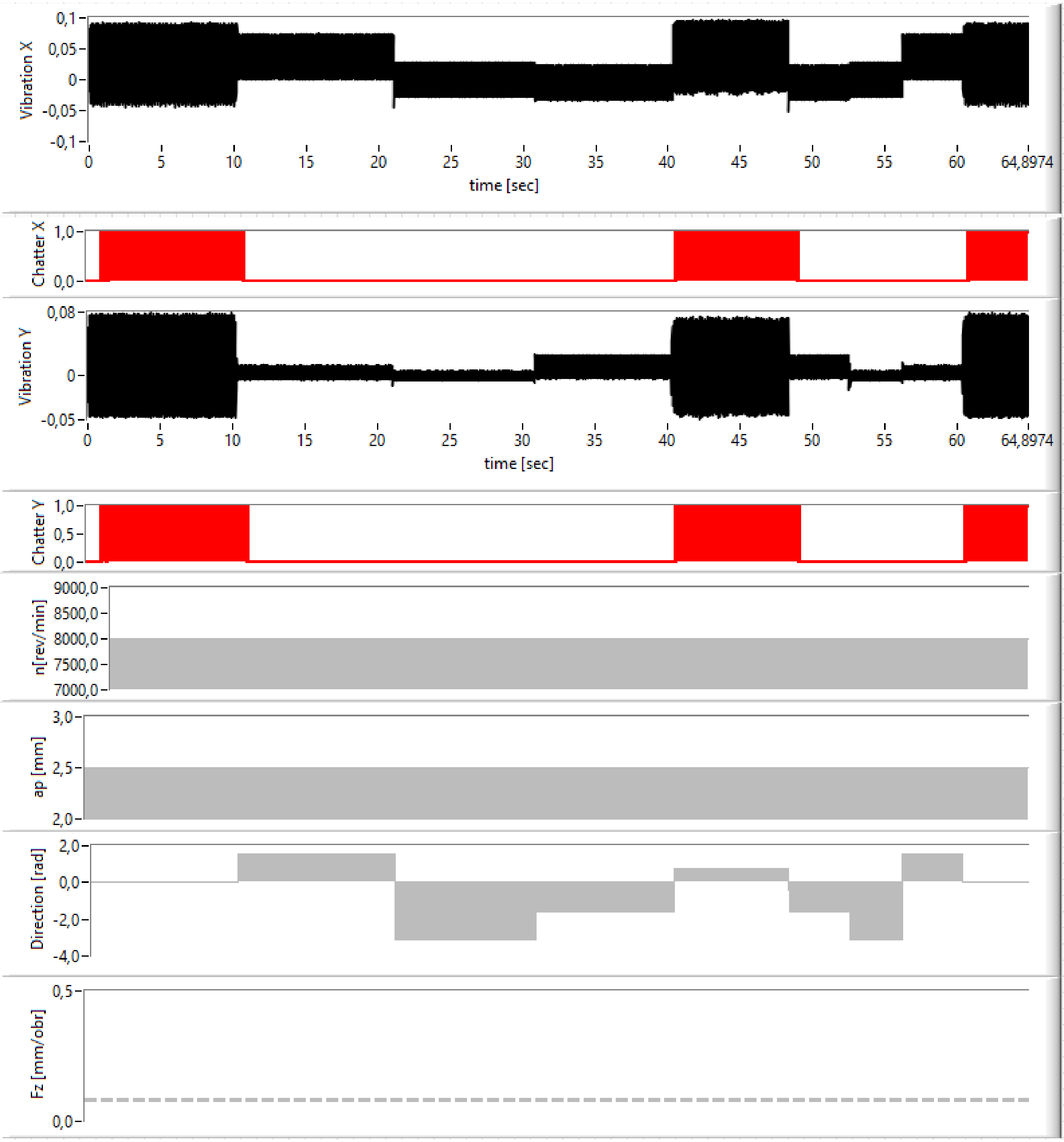


Fig. 11. Variable cutting parameters on the basis of CNC code

6. CONCLUSIONS

The developed methodology and software for dynamic modification of cutting parameters during the simulation enables simulation of any milling operation in 3D space, including ball end milling. The advantage of numerical simulation in time domain is capable to utilize any cuting edge. This allows for CNC machine code verification in the virtual environment, and detection of the potential danger of self-excited vibrations. Online detection of the chatter will be used in the near future for automatic changes of cutting parameters, thus automatic avoidance or suppression the chatter.

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