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Numerical Investigation of the Influence of Creep Feed Grinding Process on Stick–slip Vibration of the Surface Grinder Table

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In the paper, numerical analysis of frictional self–induced vibration of the table of 3G71 surface grinder has been presented. The table of the machine tool is moved along direct contact cast iron slideways and powered by the feed drive system. These investigations are carried out based on the prepared physical model of the mass – dissipative – elastic system of the grinder. This physical model is described by the equations presenting its mathematical model. The mathematical model takes into consideration the influence of the parameters of creep feed grinding on the grinder stick-slip vibration. It has been used to create the functional model for computer simulations. The results obtained from simulations show that the grinding process reduces amplitude of stick–slip vibration of the table of the grinder.

Keywords: Modeling, simulation, stick–slip vibration, feed drive system

1. Introduction

Disadvantageous phenomenon, often appearing in the straight–line motion units of machine tools is frictional self–induced vibration. It is caused by the difference between static and kinetic friction force, decreasing characteristic of sliding force friction and also the low stiffness of the feed drive system. These vibrations appear, the most often, in the range of small sliding velocities and they manifest themselves in the form of stick–slip motion. These vibrations disrupt the original trajectories of tools motion in relation to the workpiece. They cause deterioration of the machining accuracy as well as quick wear of the tools and machine tool [1], [7] and [8].

There are three properties describing the real oscillating system: inertia, elasticity and attenuation. Dissipation of the vibration energy in machine tool could occur as a result of different kind of actions like:

- it could be natural property of the machine tool structure;
- sometimes, it is an unintentional action accompanying working process;
- in the another case, it could be caused artificially by means of different kind of the vibration dampers or complex damping systems.

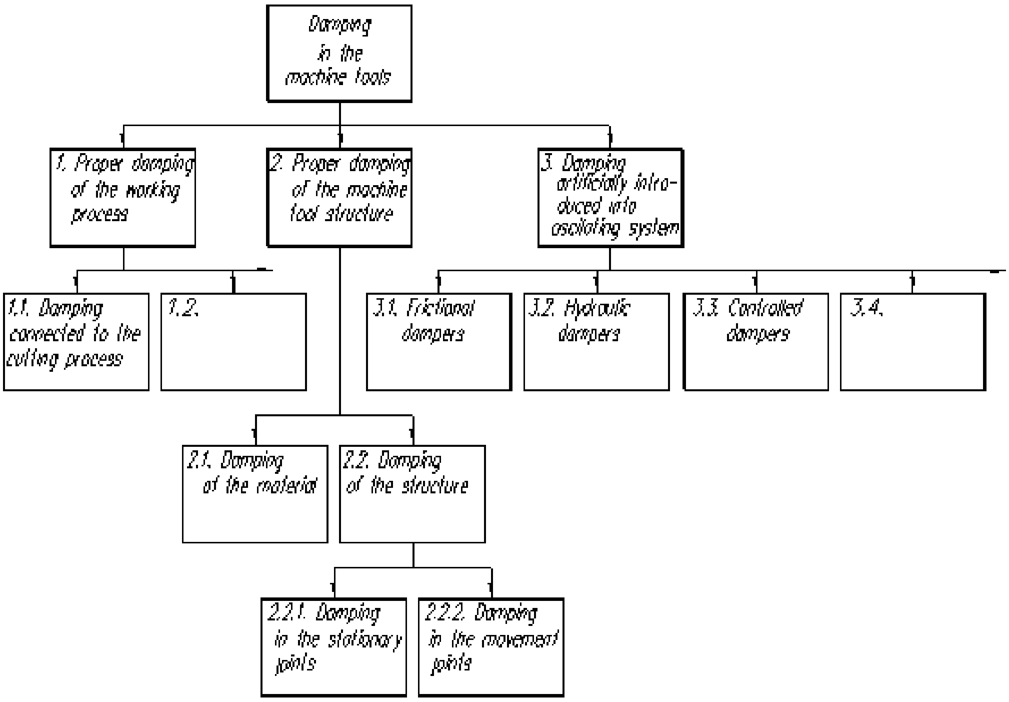

Figure 1 Classification of the mechanisms of vibration damping in the machine tools [2]

As shown in the Fig. 1, classification isn't closed and doesn't exhaust all possibilities or the ways of vibration damping in the machine tools. Blank window 1.2 could be fill up with: "controlled running of the cutting process". An adequate selection of the treatment parameters assisting by the control of table velocity could assure elimination of stick–slip vibration of the table of the grinder during creep feed surface grinding.

2. The physical model

Study of frictional vibration, being the result of friction phenomenon and creep feed grinding process on surface grinder - type 3G71, has been carried out basing on the physical model presented in the Fig. 2. This model contains massless carriage moved with the constant speed v_0 and connected to mass m_1 by the spring k_1 and damper c_1. Mass m_1 stands for the mass of grinder table along with its all moving components and slides on the surface with the conditions of contact dynamical friction, described by the force $F_d(\dot{x}_1)$. The feed drive system is replaced with the spring with coefficient of stiffness k_1 and damper with coefficient of viscous damping c_1. The chuck unit with workpiece is replaced with the mass m_2, the spring with coefficient of stiffness k_2 as well as damper with coefficient of viscous damping c_2. Furthermore the mass m_4 stands for the mass of grinding wheel with the spindle. The spring k_4 describe flexural stiffness of the spindle end. And damper c_4 is coefficient of viscous damping of the bearing unit reduced to the spindle end. Creep feed grinding is described by the massless work point, which is connected with mass m_2 and m_4 by a tangential component of cutting force F_{st} and the spring with coefficient of stiffness k_3 which models the elastic strain of grinding wheel in the contact with workpiece. The model contains some simplifications, e.g. the masses act as material particles, the model does not include perpendicular vibration.

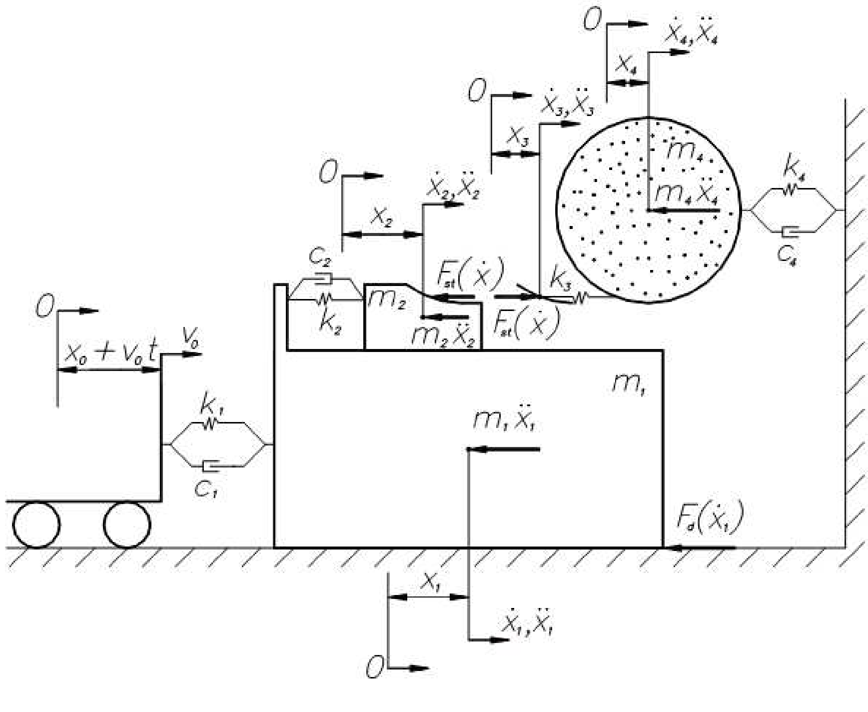

Figure 2 One–way physical model of three–mass system: grinder table – workpiece – grinding wheel

3. Mathematical model

The motion equations describing the three–mass physical model are in the following form:

- **I phase** – idle movement of grinding table (without the cutting force engaged)

$$\begin{aligned} m_1\ddot{x}_1 - c_1(v_0 - \dot{x}_1) - k_1(x_0 + v_0t - x_1) & \\ +c_2(\dot{x}_1 - \dot{x}_2) + k_2\left(x_1 - x_2\right) + F_d\left(\dot{x}_1\right) &= 0 \\ m_2\ddot{x}_2 + c_2\left(\dot{x}_2 - \dot{x}_1\right) + k_2\left(x_2 - x_1\right) &= 0 \end{aligned} \tag{1}$$

- **II phase** – during grinding process (with the cutting force engaged)

$$\begin{aligned} m_1\ddot{x}_1 - c_1(v_0 - \dot{x}_1) - k_1(x_0 + v_0t - x_1) & \\ +c_2(\dot{x}_1 - \dot{x}_2) + k_2\left(x_1 - x_2\right) + F_d\left(\dot{x}_1\right) &= 0 \\ m_2\ddot{x}_2 + c_2\left(\dot{x}_2 - \dot{x}_1\right) + k_2\left(x_2 - x_1\right) - F_{st}\left(\dot{x}\right) &= 0 \\ F_{st}\left(\dot{x}\right) - k_3\left(x_3 - x_4\right) &= 0 \\ m_4\ddot{x}_4 + k_3\left(x_4 - x_3\right) - c_4\dot{x}_4 - k_4x_4 &= 0 \end{aligned} \tag{2}$$

Tangential component of cutting force F_{st} by creep feed surface grinding has been derived from the formula [4], [5]:

$$F_{st} = 0,3b_sK\left(C_{St1}\right)^{\gamma}\left(\frac{a\dot{x}}{1000v_s}\right)^{2\varepsilon-1}(aD)^{1-\varepsilon} \tag{3}$$

where

$b_s = 20$	– width of grinding wheel [mm],
C_{st1} =8000	– density of static points on the depth z=1 [mm^{-3}],
$K = 7$	– constant [N],
$a\dot{x} = \text{const}$	– proper metal removal rate [mm^2 s^{-1}],
$a = 0.5$	– thickness of cutting layer [mm],
$\dot{x}$	– in-feed speed of table [mm s^{-1}],
$v_s = 30$	– peripheral speed of grinding wheel [m s^{-1}],
$D = 200$	– diameter of grinding wheel [mm],
$\gamma = 1$	– exponent,
$\varepsilon = 0.8$	– exponent

Friction force $F_d(\dot{x}_1)$ is described by the force-speed characteristic curve of dynamic friction in direct contact cast iron table slideways of 3G71 surface grinder. This characteristic curve is obtained by pressure of normal force F_n=2040.5 [N] resulting from table weight [3], [6] and is presented in the Fig. 3. Stiction force F_t depends on the time of restt_s and ascends along with the time t_s passage. During passing from rest to motion, friction force F decreases from the value F_t to the value F_0.

4. Functional model

Dynamic friction force $F_d(\dot{x}_1)$ is described in the functional model as follows:

$$\begin{aligned} F_d(\dot{x}_1) &= \frac{F_0}{1 + AB\dot{x}_1} \qquad \text{for} \quad \ddot{x}_1 > 0 \quad (\dot{x}_1 = 0 \div \dot{x}_{1\,\max}) \\ F_d(\dot{x}_1) &= F_d(\dot{x}_1 = \dot{x}_{1\,\max}) \qquad \text{for} \quad \ddot{x} < 0 \\ F - d(\dot{x}_1) &= F_0 \qquad \text{for} \quad \dot{x} = 0 \quad \text{and} \quad t_s = 0 \end{aligned} \tag{4}$$

where $A = 0.23$ and $B = 1.033$ – selected coefficients in order to describe the characteristic of dynamic friction.

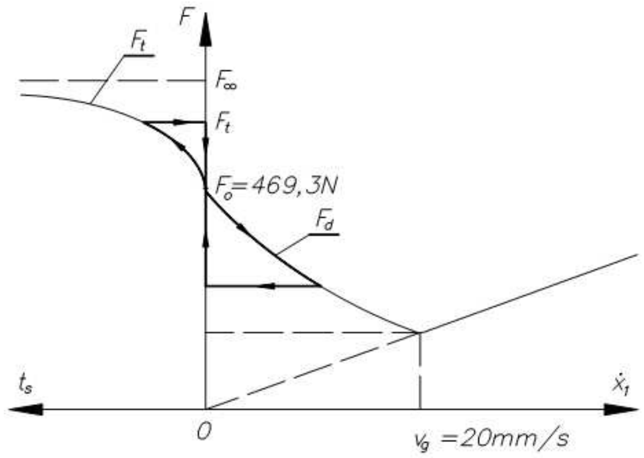

Figure 3 Force–speed characteristic curve of dynamic friction in direct contact cast iron slideways

The system of equations (1) and (2) has been put to the numerical study in Matlab–Simulink computer programme. Functional model of three-mass system is shown in the Fig. 4.

The values of coefficient of stiffness, viscous damping and masses presented in the equations (1) and (2), have been derived from experimental measurements and/or defined basing on 3G71 surface grinder technical documentation. Input parameters for numerical simulations were as follows:

$m_1 = 208$ kg	– mass of table,
$m_2 = 2$ kg	– mass of workpiece,
$m_4 = 4$ kg	– mass of grinding wheel,
$c_1 = 0.15 \cdot 10^6$ Ns/m	– coefficient of viscous damping of feed drive system,
$k_1 = 20 \cdot 10^6$ N/m	– coefficient of stiffness of feed drive system,
$c_2 = 10 \cdot 10^6$ Ns/m	– coefficient of viscous damping of workpiece chuck unit,
$k_2 = 1000 \cdot 10^6$ N/m	– coefficient of stiffness of workpiece chuck unit,
$k_3 = 5000 \cdot 10^6$ N/m	– coefficient of stiffness of elastic strain of grinding wheel in the contact with workpiece,
$c_4 = 30 \cdot 10^6$ Ns/m	– coefficient of viscous damping of bearing unit,
$k_4 = 5000 \cdot 10^6$ N/m	– coefficient of stiffness of bearing unit,
$v_0 = 1$ mm/s	– velocity of carriage,
$x_0 = 0.005$ mm	– strain of carriage.

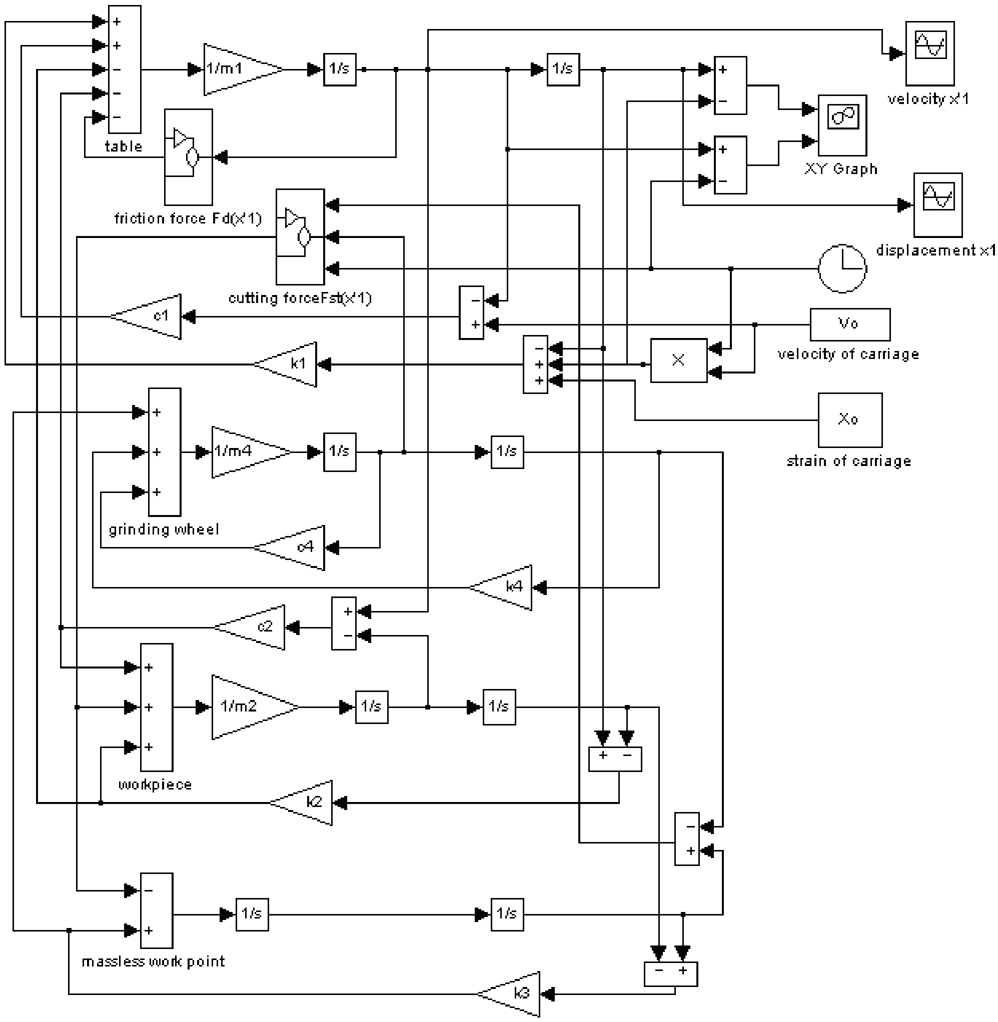

Figure 4 Complex functional model of three–mass system

5. Numerical simulations

To avoid the rapid increase of cutting force and to make the digital computation possible the cutting force has been multiplied by function:

$$2\arctan(t - t_1)/\pi \qquad (5)$$

where:

t_1 – period of time of simulation from the beginning to the start of acting of cutting force,

t – time of simulation.

The simulation programme creates characteristics of displacement x_1 and velocity $\dot{x}_1$ of mass m_1 vs time t. Fig. 5 concerns the first phase of the grinding process, without treatment.

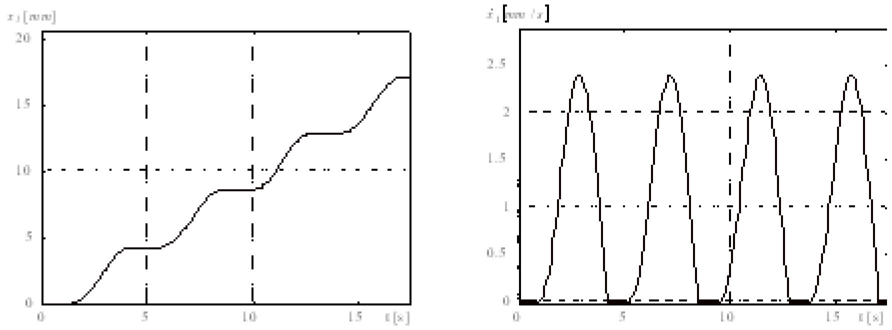

Figure 5 The curves of displacement x_1 and velocity $\dot{x}_1$ of mass m_1 vs time t without cutting forced engaged

However, Fig. 6 shows the characteristic of displacement x_1 and velocity $\dot{x}_1$ vs time t during the second phase, with the cutting force engaged. The velocity of the table approaches constant feed drive velocity $v_0 = 1$ mm/s. Results of numerical simulations are presented also in phase trajectory form of velocity $\dot{x}_1$ vs displacement x_1.

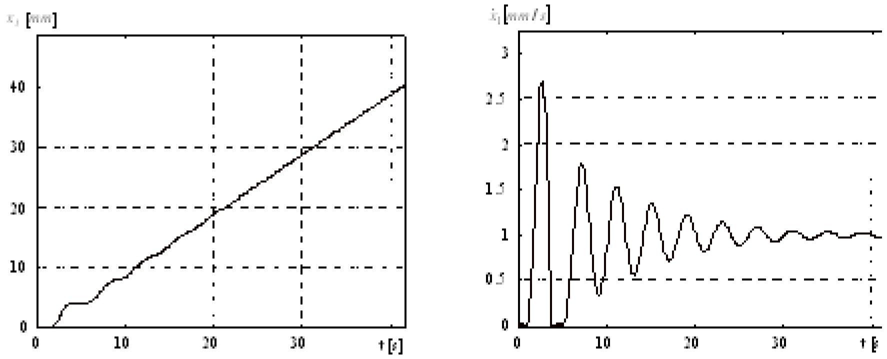

Figure 6 The curves of displacement x_1 and velocity $T\dot{x}_1$ of mass m_1 vs time t with cutting forced engaged

Fig. 7. presents the grinder's table idle movement with stick–slip vibration. Down part of the curve concerns table's stick phase. In the Fig. 8 the curve of table's velocity, which is stroking and next process working is beginning. It can be clearly noticed that grinding process generates periodic stable unit's movement approaching constant feed drive velocity $v_0 = 1$ mm/s.

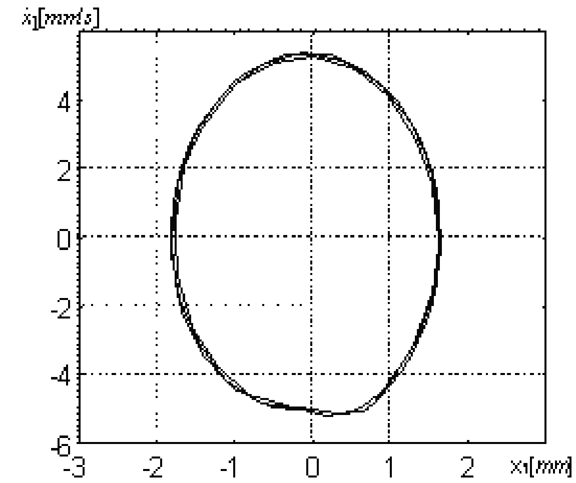

Figure 7 Phase trajectory of velocity $\dot{x}_1$ vs displacement x_1 without cutting forced engaged

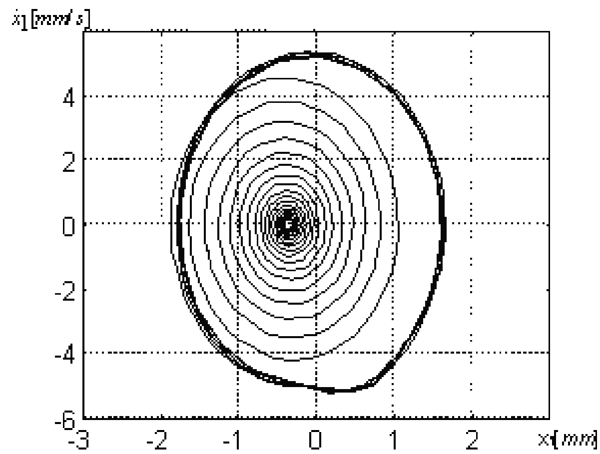

Figure 8 Phase trajectory of velocity $\dot{x}_1$ vs displacement x_1 with cutting forced engaged

6. Conclusions

Based on numerical simulations it can be stated that creep–feed grinding process is damping stick–slip vibration of feed unit. Thus, it is reducing critical velocity below which frictional self–induced vibration are appearing. Certainly, presented results must be considered qualitatively as a preliminary stage of study. They have to be verified in an experimental way.

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