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SIMULATION OF DYNAMICS OF CNC MEANDRINE TOOL MAGAZINE

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Abstract: *Article deals with analytical description of dynamical behavior of meandrine tools magazine of CNC machine. Mechanism of magazine is analyzed from the point of view of kinetic energy and mechanical power of individual parts with translational, rotational and general planar motion, and inserted tools. Magazine works in displacement, velocity and current feedback loop with velocity feedforward. The principal equation of motion of magazine is derived using method of equivalent inertia in combination with mathematical description of electric motor and PID controllers. Numerical solution of derived equations leads to determination of torque of servo-motor needed for complying of required motion dynamics. Position control error of the system is calculated as well. Weight of tools and their position within the magazine are considered as random quantities with uniform distribution. It is shown in the article that not only weight of tools but also their distribution within the magazine are important conditions influencing load of servo-motor.*

Keywords: Tool magazine, CNC machine, Dynamics of controlled system.

1. Introduction

Automatic tool changers are used as an accessory of CNC machine centers. They consist of position controlled tool magazine and automated gripper. This arrangement allows fast tool change what reduces time of non-cutting procedures and enhance productive capacity of CNC machines and machining centers (Zhongqi, 2009). Tool magazines may have different topology usually given by desired tools capacity. VÚTS company develops three types of tool changers: small size 20 beds drum type, middle size 40 beds oval shape and the largest 80 beds meandrine type. Beds are arranged into chain structure where each bad can be occupied by one tool (Fig. 1). The meandrine tools magazine is a system substructure which ensures correct positioning of a tool for the purpose of its exchange. For fast and precise positioning of tool beds a suitable servo-motor must be determined. Key parameters for correct servo-motor determination are maximum torque and mechanical power.

The dynamic behavior of tool magazine is given by load of actuator. This load is given by properties of the magazine's chain as a number of beds (chain elements), mass of each bad and moment of inertia of a bed. These properties are given by magazine design. Load of the magazine is also given by number of inserted tools, their mass, size, moment of inertia and tools distribution over the chain. These parameters are not known exactly beforehand and they are considered as random variables. Presented calculation of magazine's dynamics respects the random character of these input variables and more over a chosen deterministically defined load case is calculated as well.

2. Modelling of mechanical part

Maximum considered weight of one tool is m_{tmax} = 35 kg including chuck. Weight of the chuck ISO 50 is about 4.5 kg therefore it is considered that one bad can be loaded by mass form 5 kg to 35 kg. For simulations with consideration of random tool's weight we assume that this weight has continuous uniform distribution. Therefore the appearance of a tool in magazine with weight from specified interval has the same probability.

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Because tools make in certain phase of their path also general planar motion which consist apart from translation also from rotational motion it is necessary to take in to consideration also moment of inertia of the tool about longitudinal axes. This moment of inertia is to some extent a random variable as well but it is possible to apply some limitations. If we consider that a typical tool has more likely a cylindrical shape it is possible derive the dependency of moment of inertia of every tool on its mass.

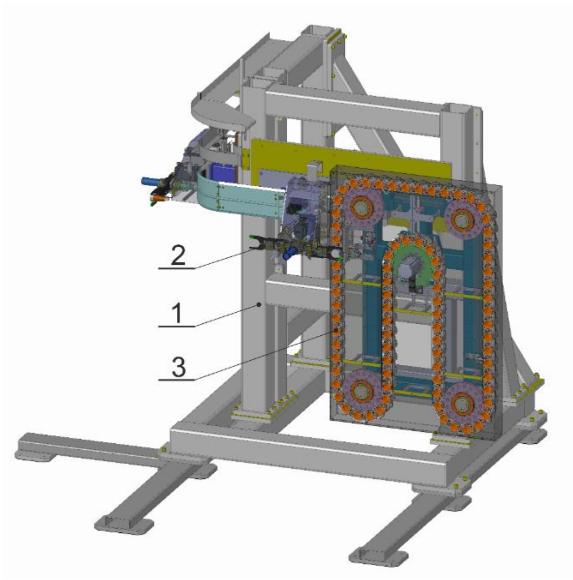


Fig. 1: CAD model of automatic tool changer (1 - testing frame (substitution for CNC machine center), 2 - grip, 3 - tool magazine).

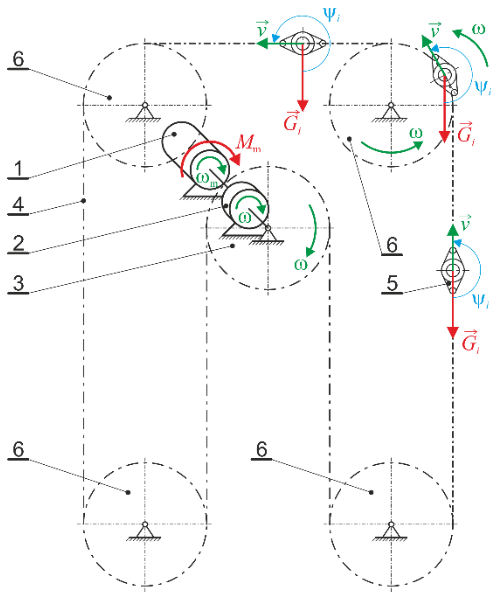


Fig. 2: Computational scheme of mechanical part (plant) (1 - motor, 2 - gear box, 3 - drive wheel, 4 - chain, 5 - chain element, 6 - pulley).

For the dynamic solution of magazine's motion the method of equivalent inertia is used and leads to derivation of principal equation of motion in form

$$M_{\mathrm{eqv}} = J_{\mathrm{eqv}}\, \alpha_{\mathrm{m}} + \frac{1}{2}\frac{\mathrm{d}J_{\mathrm{eqv}}}{\mathrm{d}\varphi_{\mathrm{m}}}\dot{\varphi}_{\mathrm{m}}^{2} \qquad (1)$$

where M_{eqv} is equivalent torque of a system and J_{eqv} is equivalent moment of inertia of a system. φ_{m}, ω_{m} and α_{m} are actual angular displacement, velocity and acceleration of the rotor of motor.

Calculation of equivalent moment of inertia J_{eqv} of the system is based on balance of kinetic energy of equivalent system and real system. The kinetic energy of real system is given by a sum of kinetic energies of its individual elements in accordance with computational scheme in Fig. 2. Certain part of kinetic energy of the magazine's system is given by kinetic energy of parts making rotational motion as motor's rotor, gear box, drive wheel and four pulleys. Another part of kinetic energy is given by motion of chain beds. Certain number of chain beds make rectilinear motion either in horizontal or vertical direction. The rest of chain beds make general planar motion. Another part of kinetic energy of magazine is made up of kinetic energy of tools. The path of every tool is tracked and it is calculated that from the total number of *n* tools inserted into the chain beads certain number of tools at certain time make rectilinear translational motion in vertical or horizontal direction and the rest of tools make general planar motion.

Calculation of equivalent torque M_{eqv} is based on calculation of mechanical power of tools. It is given by scalar multiplication of vector of velocity $\vec{v}$ and gravity force $\vec{G_i}$of every tool where ψ_i is angle between these two vectors (Fig. 2). Total mechanical power of the system comprising also the power of motor with torque M_{m}. From the equivalency of mechanical power of real and equivalent system the equivalent torque M_{eqv} is calculated from equation (2). Total mechanical power of beds of the chain is zero because the unloaded chain is in static equilibrium. Having J_{eqv} and M_{eqv} we can substitute in to principal equation motion (1).

$$M_{\mathrm{eqv}}\, \omega_{\mathrm{m}} = M_{\mathrm{m}}\omega_{\mathrm{m}} + \sum_{i=1}^{n} G_i v \cos\psi_i \qquad (1)$$

3. Modelling of motor and feedback control loop

As a driving unit the three-phase synchronous motor BMH1402P12F2A of Schneider Electric company is used. For the purpose of simulation it is possible to substitute the model of three-phase synchronous servomotor with permanent magnets in rotor for simplified model based on description of DC motor (Jirásko et al., 2015). In such a case the properties of only one solenoid are modeled and the fact that really the motor contains three solenoids is compensated by multiplying of the torque constant by 3/2, therefore $K_{\mathrm{M\ total}} = 3/2 \cdot K_{\mathrm{M}}$.

Motor of the magazine is connected in displacement, velocity and current feed-back loop (Fig. 3). In displacement feedback loop there is a proportional controller with term K_{φ}, in other two feedback loops there are PID controllers implemented and because their derivative components were finally set to zero they are in fact only PI controllers. Furthermore the velocity feedforward is used optionally gained by constant C_{ω}. In presented scheme U is a voltage, I is a current and M_{m} is an electromagnetic torque of motor, R_{S} is a stator resistance, L_{S} is stator inductance and K_{E} is back EMF constant. It is obvious that:

$$U = U_{\mathrm{E}} + R_{\mathrm{S}} I + L_{\mathrm{S}} \frac{\mathrm{d}I}{\mathrm{d}t} \tag{2}$$

$$U_{\mathrm{E}} = \omega_{\mathrm{m}} K_{\mathrm{E}} \tag{4}$$

Torque generated by motor is

$$M_{\mathrm{m}} = K_{\mathrm{M\ total}} \cdot I \tag{3}$$

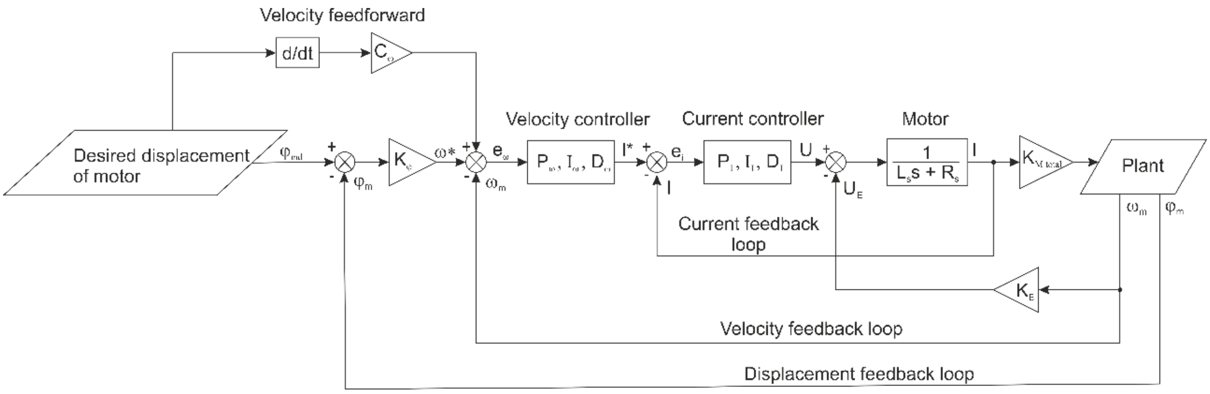
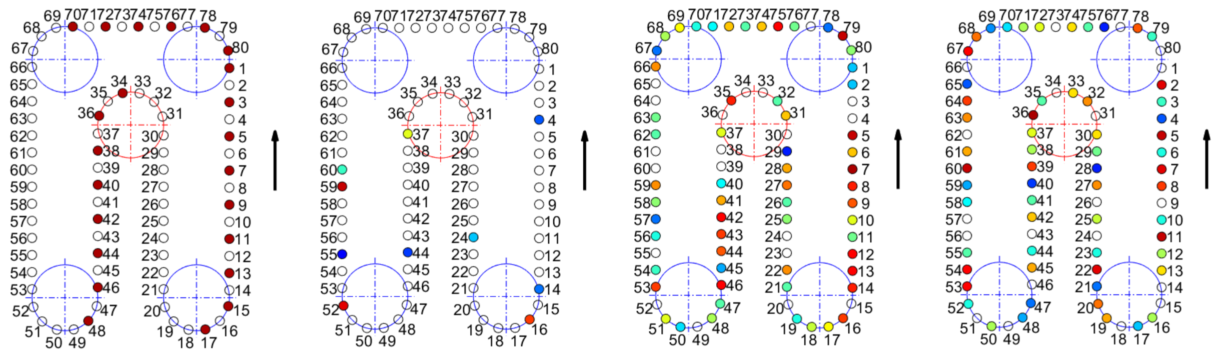


Fig.3: The scheme of feedback control of magazine plant.



a) Case 1: most inconvenient for start (realizable extreme, n=23)

b) Case 2: random distribution (n=10)

c) Case 3: random distribution (n=60)

d) Case 4: random distribution (n=60)

Range of tools weight [kg]

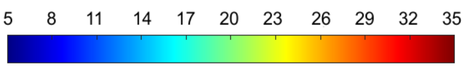


Fig. 4: Chosen cases of magazine load.

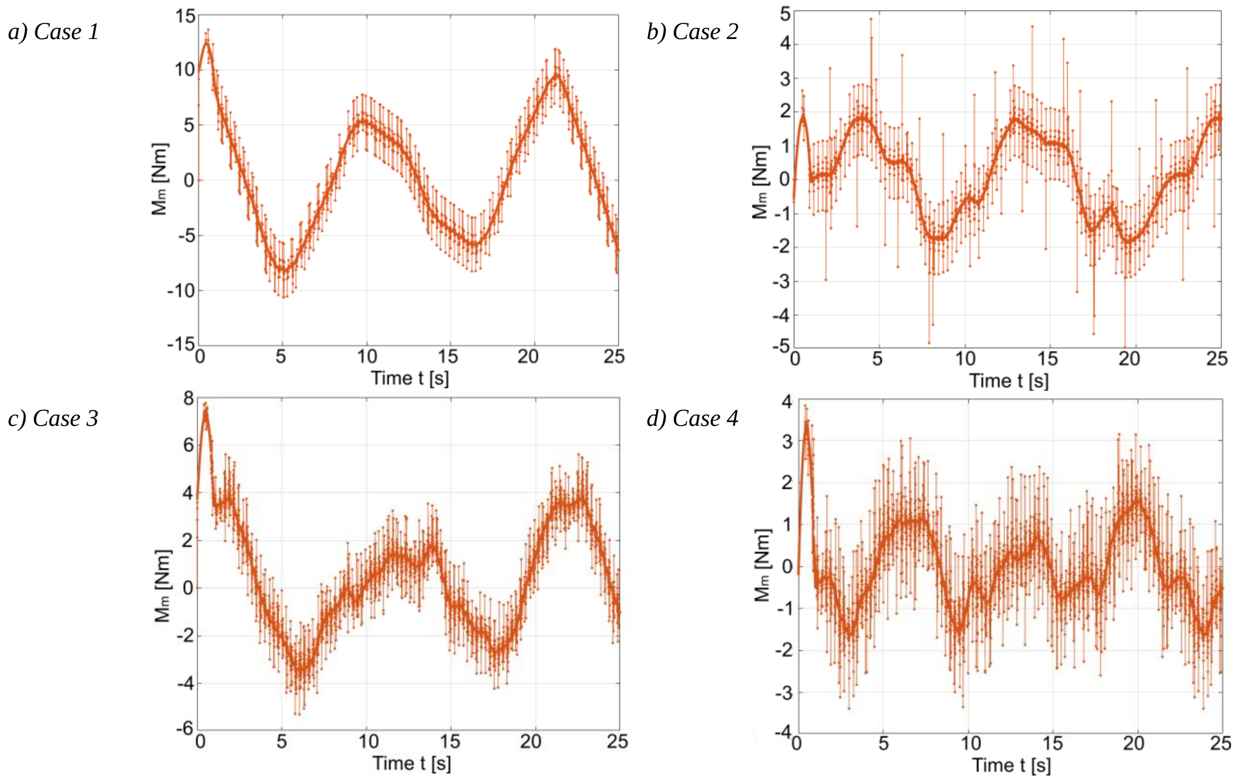


Fig. 5: Motor torque M_m calculated for chosen cases.

4. Simulations

Simulations were performed for 4 cases. Case 1 in Fig. 4 represents an extreme deterministically given distribution most inconvenient for start when 23 heaviest tools causes highest imbalance acting against direction of motor motion. Tools are inserted to every other bed because there is an assumption that tools with mass 35 kg are not possible to place just close together because of their size. Another simulation cases are for random mass and random distribution of 10 and 60 tools for instance.

5. Conclusions

From many simulations made for different conditions given either deterministically or randomly (four of them are presented in this article) follow that maximum needed torque M_m is 14 Nm and maximum power of motor P_m is 3.5 kW. This confirms that chosen servo-motor BMH1402P12F2A meets torque and power requirements for this application. The displacement control error is less 0.3 mm in starting ramp phase and less than 0.05 mm in phase of motion with constant velocity which meets requirements on precision of tools positioning. From obtained results also follows that not only weight of tools but also their distribution within the magazine are important conditions influencing load of servo-motor. This was shown for Case 3 and Case 4 when the same number of 60 tools with random mass were inserted into the magazine in random distribution (Fig. 4c and 4d, resp. Figs. 5c and 5d).

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