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COMPUTER AIDED DESIGN OF FEED DRIVES FOR CNC MACHINE TOOLS

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1. Introduction

The feed drive is one of the most important parts of every CNC machine tool. The productivity and accuracy of the CNC machine tool highly depend on its chracteristics. The feed drive main purpose is to move the working parts of machine tool (working table, tool unit, spindle unit etc.) through machine axes. A separate feed drive is necessary for every machine axis. Although, generally, feed drives have very simple kinematics structure their optimal design is problem which consists of selection of servo motor and mechanical transmission elements which must satisfy some requirements as a system.

2. Theoretical considerations and computer programs for designing feed drives for CNC machine tools

The feed drive consists of an electromotor and mechanical transmission elements. The mechanical transmission elements comprise all the machine parts which lie in the torque (power) transmission flow between the servo motor and the tool or workpiece. In different design variants the following mechanical transmission elements are most frequently used: clutches, ball lead screw and nut units, rack and pinion units, bearings, gears, gearboxes (planetary, cycloidal, harmonic), toothed belt gears, guideways etc.

The main task in the feed drive design is a selection of a servo motor and mechanical transmission components. During this process the drive angular nominal frequency ω_{od} and nominal angular frequency of the mechanical transmission elements ω_{omech} are calculated.

In order not to affect the properties of the highly dynamic AC or DC servo motor, the nominal angular frequency of the mechanical transmission ω_{omech} elements must be higher than the drive nominal angular frequency ω_{od}. According to [Stute et al. 1983; Weck 1984; Pandilov 1993]

$$\omega_{omech}/\omega_{od} \geq 2 \qquad (1)$$

is recommended. To satisfy the requirements and to enable a long exploitation period particular attention has to be paid to the selection of feed drive servomotors. An improper servo motor selection results in a less efficient operation of machine tool and a short exploitation period.

Total load torque Mtot can be calculated as:

$$Mtot = Mmf + \sum Mfl \ \ [Nm] \qquad (2)$$

where: Mmf is a torque caused by the machining force [Nm]; $\sum$Mfl is a sum of torques caused by friction and losses [Nm].

The next step is a calculation of the necessary motor speed n_e for a rapid feed rate.
The selection of a variable speed motor can be from a catalogue, or from an appropriate data base, developed during the investigation [Pandilov 1993].
The total moment of inertia Jtot can be calculated as:

$$Jtot = Jm + Jext \ [kgm^2] \qquad (3)$$

where:
Jm is a motor moment of inertia $[kgm^2]$;
Jext is an external moment of inertia reflected on motor shaft $[kgm^2]$.
Equations necessary for calculation of Mtot, n_e and Itot for different design variants are given in details in [Stute et al. 1983, Pandilov 1993].
After calculation (Mtot and n_e), for the selected servo motor an analysis of dynamic behavior must be performed.
With a dynamic behavior analysis, we calculate the acceleration time to rapid traverse feed rate for loaded motor t_a, nominal angular frequency of the drive ω_{od} and position loop gain Kv.
The acceleration time to maximal speed for loaded motor t_a can be calculated as:

$$t_a = \frac{Jtot \cdot n_m}{9.55 \cdot Ma} \cdot 10^3 = \frac{(Jm + Jext) \cdot n_m}{9.55 \cdot Ma} \cdot 10^3 \quad [ms] \qquad (4)$$

where: n_m is maximal motor speed $[min^{-1}]$; Ma is acceleration torque [Nm].
The acceleration time to maximal speed of unloaded motor t_b is:

$$t_b = \frac{Jm \cdot n_m}{9.55 \cdot Ma} \cdot 10^3 \quad [ms] \qquad (5)$$

The acceleration time to the maximal speed of unloaded motor t_b is given in a motor catalogue. If t_b is not given directly, it can be calculated indirectly by the maximal angular acceleration of the motor shaft α [rad/s^2]. Because

$$Ma = Jm \cdot \alpha \quad [Nm] \qquad (6)$$

equation (5) becomes

$$t_b = \frac{n_m}{9.55 \cdot \alpha} \cdot 10^3 \quad [ms] \qquad (7)$$

With the substitution of equation (5) in (4)

$$t_a = t_b \cdot \frac{(Jm + Jext)}{Jm} \quad [ms] \qquad (8)$$

If t_a is greater than a permitted value, corrections are made in mechanical transmission components (transmission ratio, feed screw lead etc.), in order to reduce t_a and to satisfy the necessary value.
An approximate mathematical equation of nominal angular frequency of the drive ω_{od}, is given in [Stute et al. 1983], according to the model shown in fig.1.

$$\omega od \approx \frac{1}{Teld} \cdot \left(1 + \frac{1}{2 \cdot \frac{Tmech}{Teld}} \right) \; [s^{-1}] \tag{9}$$

where: Teld is a drive electrical time constant [s];
Tmechd is a drive mechanical time constant [s].

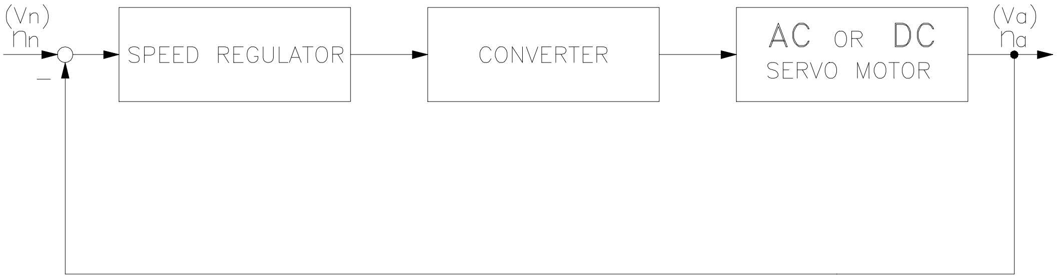

Figure 1. A block diagram of speed controlled AC or DC servo drive [Stute et al. 1983]

Another important element which can be approximately calculated is the position loop gain Kv.
The position loop gain Kv is a ratio of nominal speed v_n [m/min] and difference between nominal and actual position Δx [mm].

$$Kv = \frac{v_n}{\Delta x} \; \left[\frac{m/min}{mm} \right] \tag{10}$$

$$Kv = \frac{1000}{60} \cdot \frac{v_n}{\Delta x} \; [s^{-1}] \tag{11}$$

The analysis in [Stute et al. 1983] shows that in ideal condition the optimal value of Kv must lie in the range of:

$$0.2 \cdot \omega od \leq Kv \leq 0.3 \cdot \omega od \tag{12}$$

For real conditions it is recommended:

$$Kv < (0.2\text{-}0.3) \cdot \omega od \tag{13}$$

The calculated values for Kv from equations (12) and (13) are approximate. The exact value can be obtained experimentally during the fine tuning procedure of the drives [Pandilov 1993; Pandilov and Dukovski 1995a,1995b,1999; Kakino et al. 1994, 1995].
One of the most important requirements for good dynamic behavior of the feed drive is high acceleration of the CNC machine tool slide due to the demand for minimal mechanical time constant [Stute et al. 1983; Motika and Ciglar 1986; Pandilov 1993]. Magnitude of inertial forces which directly affect the accuracy depends on the magnitude of slide acceleration.
Acceleration limits are recommended [Stute et al. 1983; Motika and Ciglar 1986; Pandilov 1993]:

- for machine tools with normal accuracy (a_{per} = 0.8-1.5 m/s^2),
- for machine tools with greater accuracy (a_{per} = 0.2-0.4 m/s^2).

For the already selected type of servo motor, with corrections of some elements of mechanical transmission (transmission ratio, feed screw lead etc.), a higher acceleration of the machine slide using the appropriate optimization procedure may be obtained.
The acceleration of the machine slide is given as:

$$a = \frac{dv}{dt} \quad [m/s^2] \tag{14}$$

For the variant with a ball feed screw and nut:

$$a = \alpha_1 \cdot \frac{h \cdot i}{2\pi} \quad [m/s^2] \tag{15}$$

and for the rack and pinion variant:

$$a = \alpha_1 \cdot r_p \cdot i \quad [m/s^2] \tag{16}$$

where: v is a rapid traverse feed rate [m/min]; h is a feed screw lead [m]; r_p is a radius of the pinion [m]; i is a transmission ratio; α_1 is an angular acceleration of the loaded motor shaft $[rad/s^2]$.
The angular acceleration of loaded motor shaft α_1 is

$$\alpha_1 = \frac{Ma}{Jtot} \quad [rad/s^2] \tag{17}$$

where: Ma-is an acceleration torque of the selected motor [Nm].
In that case equations (15) and (16) are transformed into:

$$a = \frac{Ma}{Jtot} \cdot \frac{h \cdot i}{2\pi} \quad [m/s^2] \tag{18}$$

$$a = \frac{Ma}{Jtot} \cdot r_p \cdot i \quad [m/s^2] \tag{19}$$

The optimization of a transmission ratio i, feed screw lead h or radius of the rack pinion r_p will be done by using the following procedure:
1. For every standard value of the feed screw lead h or radius of the pinion r_p the transmission ratio range $i_1 \le i \le < i_2$ should be calculated in order to satisfy the following conditions:

- the calculated necessary motor speed n_e for the desired rapid traverse feed rate must be smaller or equal to the maximum motor speed n_m ($n_e \le n_m$),
- the total load torque Mtot must be smaller or equal to the nominal motor torque Mn (Mtot≤Mn).

2. In the range $[i_1, i_2]$ the maximum of the function of acceleration a=f(i) at constant h or r_p should be found:

$$\max\{a(i)\} = \max\{a(i_1), a(i_2), a(e_1), \ldots, a(e_j)\} \tag{20}$$

where $e_1, \ldots, e_j$ are extremes in the range $[i_1, i_2]$.
The extremes can be found by the equation

$$\frac{da(i)}{di} = 0 \tag{21}$$

The function of the acceleration a=f(i) in the range $[i_1, i_2]$ may have one, more or no extremes (fig.2.).

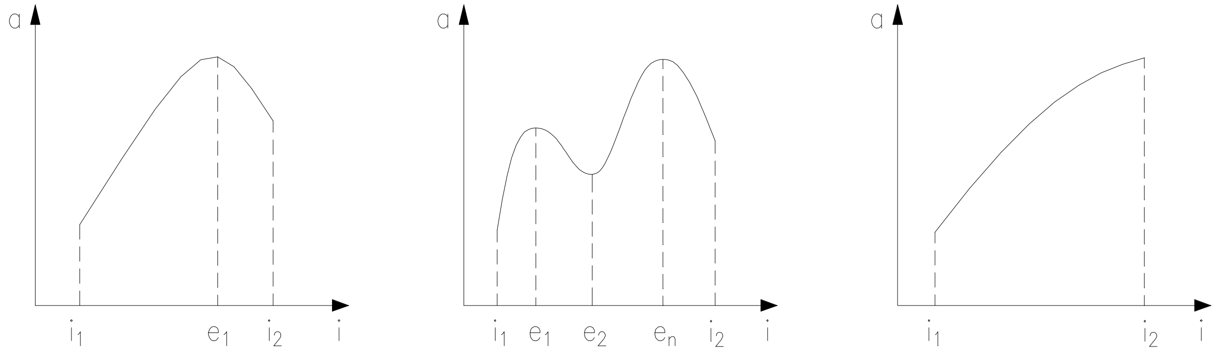

Figure 2. Possible forms of the function of acceleration

When the function of acceleration a=f(i) gets a maximal value for the constant feed screw lead h or radius of the pinion r_p the transmission ratio obtains the relative optimal value i_{op}.

3. To get the absolute optimum of the transmission ratio i_{opt} and optimal values of the feed screw lead h_{opt} or of the pinion radius r_{opt} procedures described above in 1 and 2 for all standard values for h and r_p should be repeated n times. In that way could be obtained n relative optimal transmission ratios i_{opi} for the appropriate n different standard values for h_i or r_{pi}, where i=1,...,n.

The pair (i_{opi},h_i) or (i_{opi},r_{pi}) that gives the maximal value for the acceleration function, will provide the absolute optimum for the transmission ratio i_{opt}, and, the optimal value for the feed screw lead h_{opt} or for the radius of the pinion r_{opt}.

It means

$$\max\{a(i_{op},h)\}=\max\{a(i_{op1},h_1),...,a(i_{opn},h_n)\} \tag{22}$$

or

$$\max\{a(i_{op},r_p)\}=\max\{a(i_{op1},r_{p1}),...,a(i_{opn},r_{pn})\} \tag{23}$$

Using equations (22) and (23) the pair (i_{opt},h_{opt}) or (i_{opt},r_{opt}) is obtained which provides a maximal value for the function a=f(i).

This optimization procedure is different from procedures shown in [Stute et al. 1983; Motika and Ciglar 1986], where the relative optimal transmission ratio i_{op} is calculated using equation (21) without taking in consideration that $n_e \leq n_m$ and $M_{tot} \leq M_n$.

The theoretical assumptions treated in the text above, are implemented in the computer program, written for PC in C language.

3. Conclusion

The created programs for servo motor selection and optimization of the feed drives mechanical transmission structure enable an efficient interactive and optimal design of CNC machine feed drives. The presented software also reduces the design time and modernizes the design process.

References

Kakino, Y., Matsubara, A., Li, Z., Ueda, D., Nakagawa, H., Takeshita, T., Maruyama, H., "A study of the Total Tuning of the Feed Drive System in NC Machine Tools (1st Report)-Modeling of Feed Drive Mechanism and Identification of the Parameters", Journal of the Japan Society of Precision Engineering, Vol.60, No.8, 1994, pp 1097-1101.

Kakino, Y., Matsubara, A., Li, Z., Ueda, D., Nakagawa, H., Takeshita, T., Maruyama, H., "A study of the Total Tuning of the Feed Drive System in NC Machine Tools (2nd Report)-Single Axis Servo Parameter Tuning", Journal of the Japan Society of Precision Engineering, Vol.61, No.2, 1995, pp 268-272.

Motika, R., Ciglar, D., "Optimization of feed drives for NC machine tools", Strojarstvo, Vol.28, No.4, 1986, *pp 229-233. (In Croatian).*

Pandilov, Z., "Computer Aided Design of regulated drives for NC machine tools", M.Sc.Thesis, Faculty of Mechanical Engineering, Skopje, Macedonia, 1993. (In Macedonian).

Pandilov, Z., Dukovski, V., " One approach towards analytical calculation of the position loop gain for NC machine tools", Proceedings of the 3rd Conference on Production Engineering, CIM'95, 23/24 November, Zagreb, Croatia, 1995a, pp G77-G83.

Pandilov, Z., Dukovski,V., Dudeski Lj., "Computer programs for designing NC machine tool drives", II Konferencja Naukowa" Komputerowe Wspomaganie Prac Inzynierskich", Proceedings of the Conference, 7-8.12.1995, Szklarska Poreba, Poland, 1995b, pp 265-271.

Pandilov, Z., Dukovski, "CAD for CNC machine tool main spindle and feed drives", Preprints of the 14th World IFAC Congress,International Federation Of Automatic Control,Volume A (Manufacturing, Social Effects, Scheduling), Bejing, P.R.China, July 5-9, 1999, pp 31-36.

Push, V., E., "Machine tools", Machinostroenie, Moscow, 1986. (In Russian).

Stute, G., Bobel, K., Hesselbach, J., Hode, U., Stof, P.," Electrical feed drives for machine tools", Edited by Hans Gross, John Wiley & Sons, Chichester, 1983.

Weck, M., "Handbook of Machine Tools", Volume 3, Automation and Controls, John Wiley & Sons, Chichester, 1984.

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