

COMPUTER AIDED OPTIMAL CNC MACHINE TOOLS SERVO DRIVES DESIGN

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Abstract: One of the most important requirements for good dynamic behaviour of the feed drive is high acceleration of the CNC machine tool slide due to the demand for minimal mechanical time constant. The servo drive is one of the most important parts of every CNC machine tool. Generally servo drives for CNC machine tools have a very simple kinematic structure. But the optimal servo drives design is a problem which consists of an appropriate selection of AC or DC motors and mechanical transmission elements, which must satisfy some conditions as a system. Because of the extensive calculations and optimization algorithms, original computer programs are developed. 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 servo drives. The presented software also reduces the design time and modernizes the design process.

Keywords: servo drives, CNC machine tools, Computer Aided Design, optimal

1. INTRODUCTION

The servo drive is one of the most important parts of every CNC machine tool [1–9]. The productivity and accuracy of the CNC machine tool highly depend on its characteristics [1–6,9]. The servo drive main purpose is to move the working parts of machine tool (working table, tool unit, spindle unit etc.) through machine axes. A separate servo drive is necessary for every machine axis. Although, generally, servo 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 [2–6,9].

2. THEORETICAL CONSIDERATIONS AND COMPUTER PROGRAMS FOR DESIGNING SERVO 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 (figure 1) 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 [2–6]

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

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 M_{tot} can be calculated as:

$$M_{tot} = M_{mf} + \sum M_{fl} \quad [Nm] \quad (2)$$

where: M_{mf} is a torque caused by the machining force [Nm]; $\sum M_{fl}$ 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 [6].

The total moment of inertia J_{tot} can be calculated as:

$$J_{tot} = J_m + J_{ext} \quad [kgm^2] \quad (3)$$

where: J_m is a motor moment of inertia [kgm²]; J_{ext} is an external moment of inertia reflected on motor shaft [kgm²].

Equations necessary for calculation of M_{tot} , n_e and l_{tot} for different design variants are given in details in [2–5,9]. After calculation (M_{tot} 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 K_v .

The acceleration time to maximal speed for loaded motor t_a can be calculated as:

$$t_a = \frac{J_{tot} \cdot n_m \cdot 10^3}{9.55 \cdot M_a} = \frac{(J_m + J_{ext}) \cdot n_m \cdot 10^3}{9.55 \cdot M_a} \quad [ms] \quad (4)$$

where: n_m is maximal motor speed [min^{-1}]; M_a is acceleration torque [Nm].

The acceleration time to maximal speed of unloaded motor t_b is:

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

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

$$M_a = J_m \cdot \alpha \quad [Nm] \quad (6)$$

equation (5) becomes

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

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

$$t_a = t_b \cdot \frac{(J_m + J_{ext})}{J_m} \quad [ms] \quad (8)$$

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 [2,3,4,5,6], according to the model shown in figure 2.

$$\omega_{od} \approx \frac{1}{T_{eld}} \cdot \left(1 + \frac{1}{2 \cdot \frac{T_{mech}}{T_{eld}}} \right) \quad [s^{-1}] \quad (9)$$

where: T_{eld} is a drive electrical time constant [s]; T_{mech} is a drive mechanical time constant [s].

Another important element which can be approximately calculated is the position loop gain K_v .

The position loop gain K_v is a ratio of nominal speed v_n [m/min] and difference between nominal and actual position Δx [mm].

$$K_v = \frac{v_n}{\Delta x} \quad \left[\frac{\text{m/min}}{\text{mm}} \right] \quad (10)$$

$$K_v = \frac{1000}{60} \cdot \frac{v_n}{\Delta x} \quad [s^{-1}] \quad (11)$$

The analysis in [2–5] shows that in ideal condition the optimal value of K_v must lie in the range of:

$$0.2 \cdot \omega_{od} \leq K_v \leq 0.3 \cdot \omega_{od} \quad (12)$$

For real conditions it is recommended:

$$K_v < (0.2-0.3) \cdot \omega_{od} \quad (13)$$

The calculated values for K_v from equations (12) and (13) are approximate. The exact value can be obtained experimentally during the fine tuning procedure of the drives [6,10–17].

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 [2–5,11]. Magnitude of inertial forces which directly affect the accuracy depends on the magnitude of slide acceleration. Acceleration limits are recommended [2–5,9,11]:

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

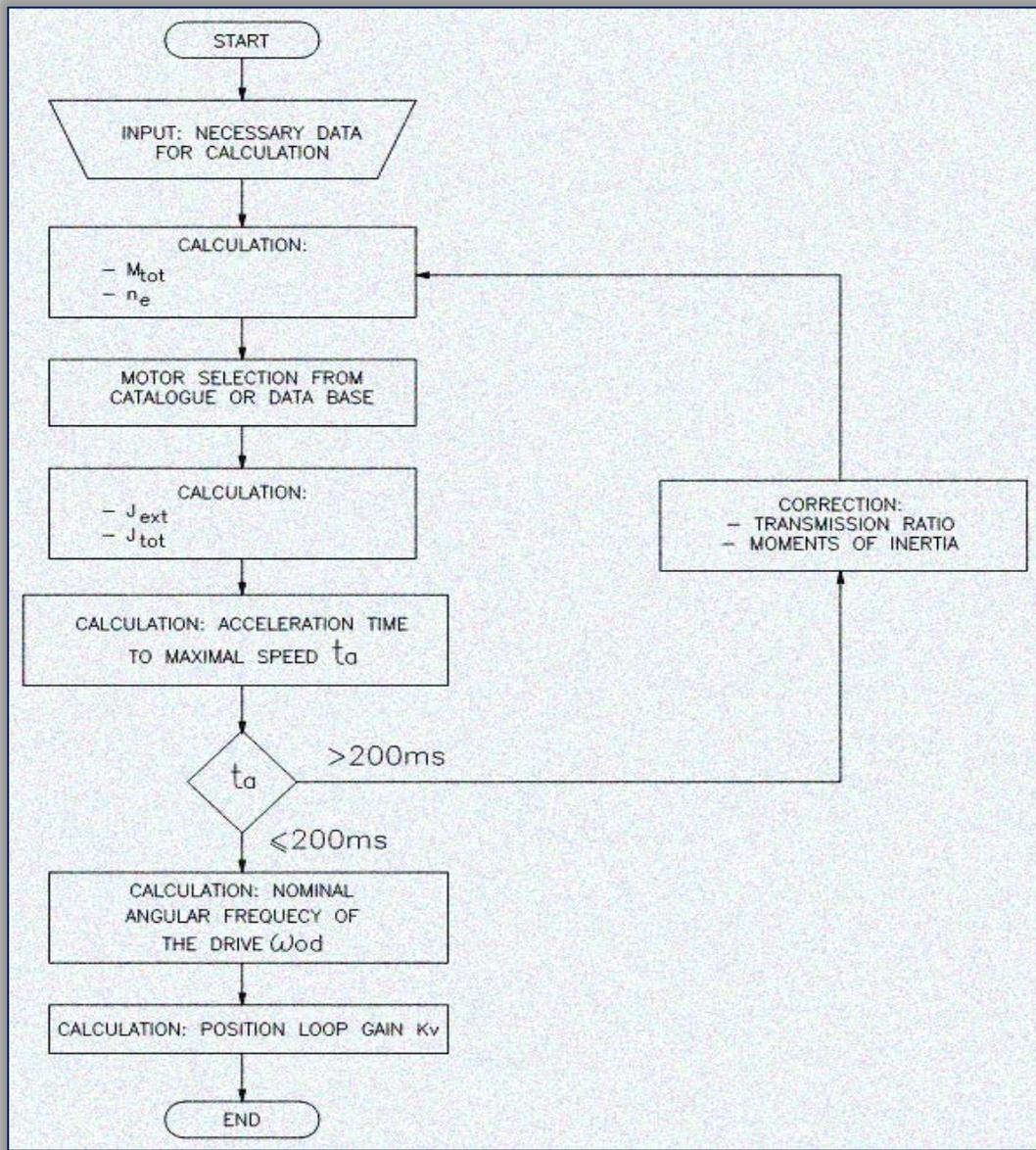


Figure 1. A feed drive servo motor selection flow

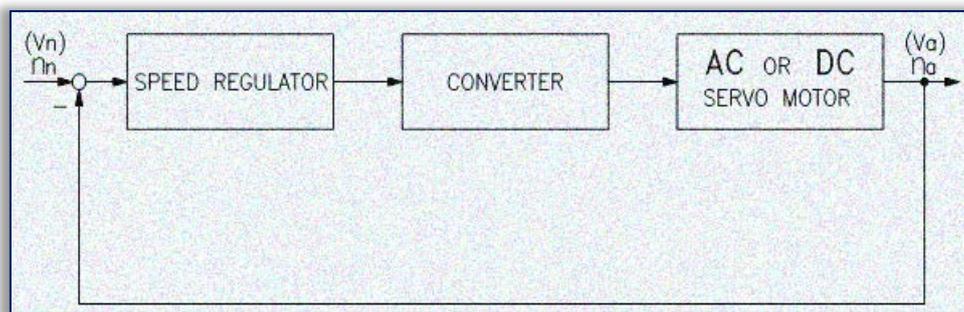


Figure 2. A block diagram of speed controlled AC or DC servo drive [8]

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:

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

For the variant with a ball feed screw and nut:

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

and for the rack and pinion variant:

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

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/s²].

The angular acceleration of loaded motor shaft α_1 is

$$\alpha_1 = \frac{M_a}{J_{\text{tot}}} \quad [\text{rad/s}^2] \quad (17)$$

where: M_a —is an acceleration torque of the selected motor [Nm].

In that case equations (15) and (16) are transformed into:

$$a = \frac{M_a}{J_{\text{tot}}} \cdot \frac{h \cdot i}{2\pi} \quad [\text{m/s}^2] \quad (18)$$

$$a = \frac{M_a}{J_{\text{tot}}} \cdot r_p \cdot i \quad [\text{m/s}^2] \quad (19)$$

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:

- For every standard value of the feed screw lead h or radius of the pinion r_p the transmission ratio range $i_1 \leq i \leq i_2$ 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 ($n_e \leq n_m$),
 - ≡ the total load torque M_{tot} must be smaller or equal to the nominal motor torque M_n ($M_{\text{tot}} \leq M_n$).
- 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:

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

where e_1, \dots, e_j are extremes in the range $[i_1, i_2]$.

The extremes can be found by the equation

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

The function of the acceleration $a=f(i)$ in the range $[i_1, i_2]$ may have one, more or no extremes (figure 3).

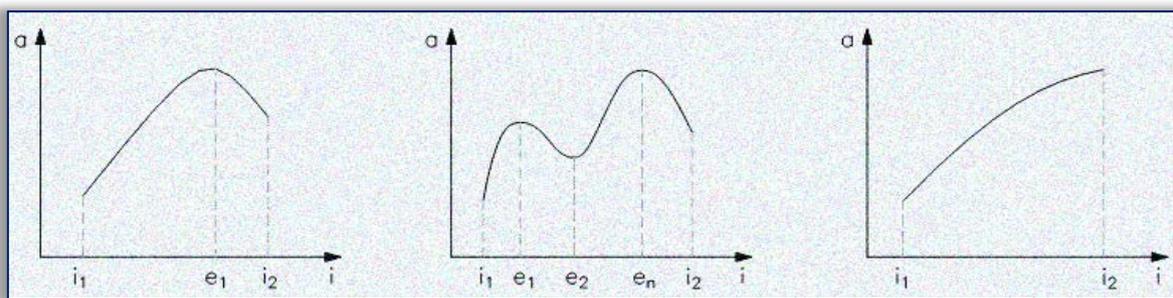


Figure 3. Possible forms of the function of acceleration

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_{opt} .

- 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 $i_{\text{opt}i}$ for the appropriate n different standard values for h_i or r_{pi} , where $i=1, \dots, n$.

The pair $(i_{\text{opt}i}, h_i)$ or $(i_{\text{opt}i}, r_{pi})$ 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} .

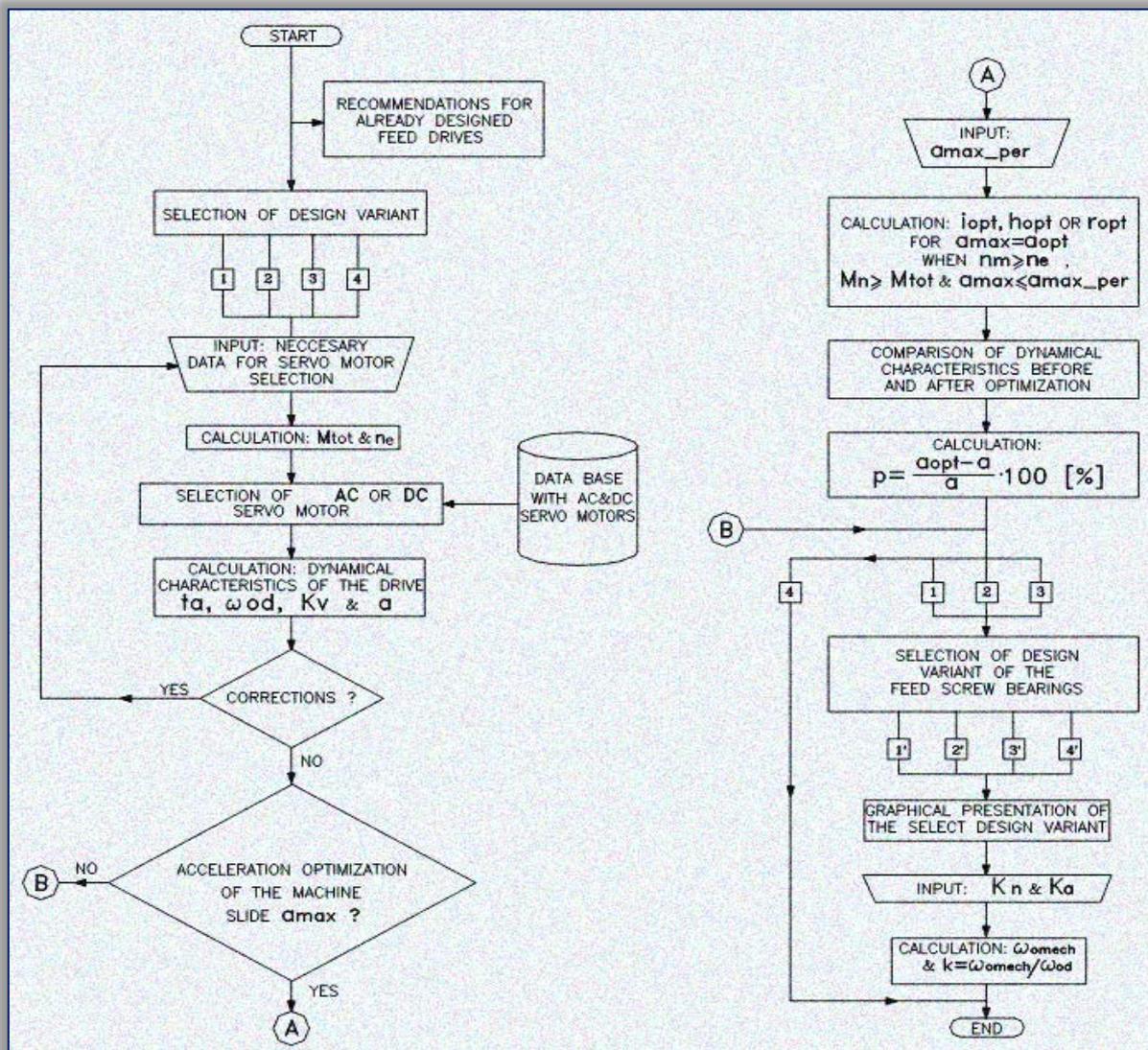


Figure 4. Flow chart of a computer program for a servo motor selection and optimization of mechanical transmission structure

It means

$$\max\{a(iop,h)\}=\max\{a(iop1,h1),\dots,a(iopn,hn)\} \quad (22)$$

or

$$\max\{a(iop,rp)\}=\max\{a(iop1,rp1),\dots,a(iopn,rpn)\} \quad (23)$$

Using equations (22) and (23) the pair $(iopt, hopt)$ or $(iopt, ropt)$ is obtained which provides a maximal value for the function $a=f(i)$.

This optimization procedure is different from procedures shown in [2–5], where the relative optimal transmission ratio iop is calculated using equation (21) without taking in consideration that $ne \leq nm$ and $Mtot \leq Mn$.

The theoretical assumptions treated in the text above, are implemented in the computer program, written for PC in C++ language [18]. Figure 4 shows a flow chart of the computer program.

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 servo drives. The presented software also reduces the design time and modernizes the design process.

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ISSN 1584 – 2665 (printed version); ISSN 2601 – 2332 (online); ISSN-L 1584 – 2665
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