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Zoran PANDILOV[1]
Vladimir DUKOVSKI[1]

COMPUTER AIDED OPTIMAL DESIGN OF SERVO DRIVES FOR CNC MACHINE TOOLS

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.

1. INTRODUCTION

The servo 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 characteristics. 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. THEORETICAL CONSIDERATIONS AND COMPUTER PROGRAMS FOR DESIGNING SERVO DRIVES FOR CNC MACHINE TOOLS

The servo 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:

[1] University “Sv. Kiril i Metodij”-Skopje, Faculty of Mechanical Engineering, Karpos II b.b., P.O.Box 464, MK-1000, Skopje, Republic of MACEDONIA, Tel.: 38923099259, Fax: 38023099298, E-mail: panzo@mf.edu.mk

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 servo drive design is a selection of a servo motor and mechanical transmission components. During this process the drive angular nominal frequency ωod and nominal angular frequency of the mechanical transmission elements ωomech 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 ωomech elements must be higher than the drive nominal angular frequency ωod. According to [1,6,9] is recommended.

$$\omega omech/\omega od \geq 2 \quad (1)$$

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:

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

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

The next step is a calculation of the necessary motor speed ne 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 Jtot can be calculated as:

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

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, ne and Itot for different design variants are given in details in [1,6].

After calculation (Mtot and ne), 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 ta, nominal angular frequency of the drive ωod and position loop gain Kv.

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

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

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

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

$$tb = \frac{Jm \cdot n_m}{9.55 \cdot Ma} \cdot 10^3 \quad [ms] \tag{5}$$

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

$$Ma = Jm \cdot \alpha \quad [Nm] \tag{6}$$

equation (5) becomes

$$tb = \frac{n_m}{9.55 \cdot \alpha} \cdot 10^3 \quad [ms] \tag{7}$$

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

$$ta = tb \cdot \frac{(Jm + Jext)}{Jm} \quad [ms] \tag{8}$$

If ta is greater than a permitted value, corrections are made in mechanical transmission components (transmission ratio, feed screw lead etc.), in order to reduce ta and to satisfy the necessary value.

An approximate mathematical equation of nominal angular frequency of the drive ωod, is given in [1], according to the model shown in Fig.1.

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

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

Tmechd is a drive mechanical time constant [s].

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 vn [m/min] and difference between nominal and actual position Δx [mm].

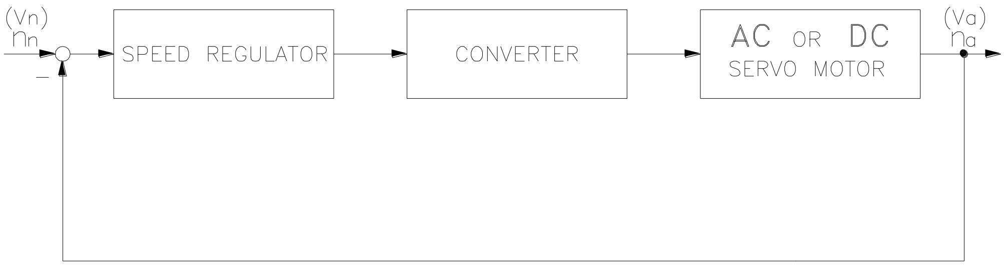

Fig. 1. A block diagram of speed controlled AC or DC servo drive [1]

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

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

(11)

The analysis in [1] shows that in ideal condition the optimal value of Kv must lie in the range of:

$$0.2 \cdot \omega od \le Kv \le 0.3 \cdot \omega od \quad (12)$$

For real conditions it is recommended:

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

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 [2,3,4,6,7,8].

One of the most important requirements for good dynamic behavior of the servo drive is high acceleration of the CNC machine tool slide due to the demand for minimal mechanical time constant [1,5,6]. Magnitude of inertial forces which directly affect the accuracy depends on the magnitude of slide acceleration.

Acceleration limits are recommended [1,5,6]:

-for machine tools with normal accuracy (aper = 0.8-1.5 m/s^2),

-for machine tools with greater accuracy (aper = 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:

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

and for the rack and pinion variant:

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

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_l is an angular acceleration of the loaded motor shaft $[rad/s^2]$.

The angular acceleration of loaded motor shaft α_l is

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

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 i1≤i≤<i2 should be calculated in order to satisfy the following conditions:

-the calculated necessary motor speed ne for the desired rapid traverse feed rate must be smaller or equal to the maximum motor speed nm (ne≤nm),

-the total load torque Mtot must be smaller or equal to the nominal motor torque Mn (Mtot≤Mn).

2. In the range [i1,i2] the maximum of the function of acceleration a=f(i) at constant h or r_p should be found:

$$\max\{a(i)\}=\max\{a(i1),a(i2),a(e1),.....,a(ej)\} \quad (20)$$

where e1,.....,ej are extremes in the range [i1,i2].

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 [i1,i2] may have one, more or no extremes (Fig. 2.).

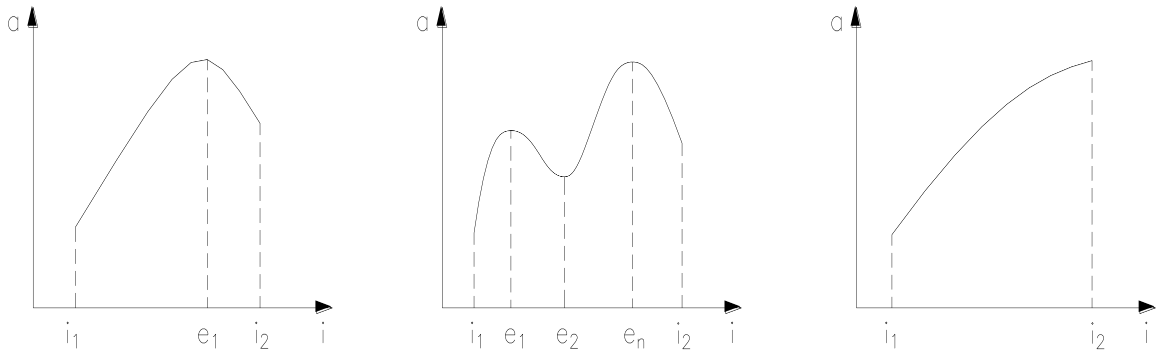

Fig. 2. Possible forms of the function of acceleration

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 iop.

3. To get the absolute optimum of the transmission ratio iopt and optimal values of the feed screw lead hopt or of the pinion radius ropt 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 iopi for the appropriate n different standard values for hi or rpi, where i=1,...,n.

The pair (iopi,hi) or (iopi,rpi) that gives the maximal value for the acceleration function, will provide the absolute optimum for the transmission ratio iopt, and, the optimal value for the feed screw lead hopt or for the radius of the pinion ropt.

It means

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

or

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

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 [1,5], 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.

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.

REFERENCES

[1] GROSS H., HAMANN J., WIEGAERTNER G., *Electrical Feed Drives in Automation: Basic, Computation, Dimensioning,* MCD Corporate Publishing, Erlangen and Munich, 2001.

[2] 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)-Modelling of Feed Drive Mechanism and Identification of the Parameters*, Journal of the Japan Society of Precision Engineering, Vol. 60, No. 8, 1994, 1097-1101.

[3] 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, 268-272.

[4] 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 (4th Report)-Multiple Axes Tuning,* Journal of the Japan Society of Precision Engineering, Vol. 63, No.3, 1997, 368-372.

[5] MOTIKA, R., CIGLAR, D., *Optimization of feed drives for NC machine tools,* Strojarstvo, Vol. 28, No.4, 1986, 229-233. (In Croatian).

[6] PANDILOV, Z., *Computer Aided Design of regulated drives for NC machine tools*, M.Sc.Thesis, Faculty of Mechanical Engineering, Skopje, Macedonia, (In Macedonian), 1993.

[7] PANDILOV Z., DUKOVSKI V., *Computer aided design of numerically controlled machine tools drives,* Annals of DAAAM for 2006 & Proceedings of the 17th INTERNATIONAL DAAAM SYMPOSIUM "Intelligent Manufacturing & Automation: Focus on Mechatronics & Robotics", 8-11th November, Vienna, Austria, 2006, 283-284.

[8] PANDILOV Z., DUKOVSKI V., *Analytical calculation of the CNC machines position loop gain*, Journal of Achievements in Materials and Manufacturing Engineering, Vol. 23, Issue 1, July 2007, 71-74.

[9] WECK M., Werkzeugmaschinen und Fertigungssysteme, Band 3, Mechatronisch Systeme: *Vorschubantriebe and Processdiagnose,* Springer, 2001.