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# COMPUTER AIDED SYSTEM FOR DESIGNING OF NUMERICALLY CONTROLLED MACHINE TOOLS MAIN SPINDLE DRIVES
# POČÍTAČOVÝ NÁVRH HLAVNÍHO HNACÍHO VŘETENE CNC OBRÁBĚCÍHO STROJE

**Abstract**

Characteristics of main spindle drives highly depends upon skillfulness of composing motors and mechanical transmission elements. This paper gives short description of an original computer program which enables interactive design of main spindle drives for CNC machine tools and analysis of different design variants.

**Abstrakt**

Charakteristika pohonu hlavního vřetene závisí zejména, jak přesně jsou složeny motorové a mechanické přenosové části. Tento článek v krátkosti popisuje originální počítačový program, který umožňuje interaktivní design hlavní vřetene pro CNC obráběcí stroje a analýzu různých navržených variant.

## 1 INTRODUCTION

The object of this paper is to present our investigation of principles for analysis and design of CNC machine tool main spindle drives. Main spindle drives analysis and design are very seldom presented in the literature.

Contemporary development in machine tools is connected with improvements in drive systems.

A special characteristic of CNC machine tool drives is application of variable speed (AC or DC) motors which provide continuos changing of cutting speeds.

Application of variable speed motors created a question of their appropriate composing with mechanical transmission elements in order to get better output characteristics of the main spindle.

## 2 CHARACTERISTICS OF THE MAIN SPINDLE DRIVES FOR NUMERICALLY CONTROLLED MACHINE TOOLS

Main spindle drives for CNC machine tools must provide constant power at wide range of speeds on the output of the main spindle. They consist of three parts: 1. variable speed motor, 2. mechanical transmission elements which provide appropriate output characteristics of the main spindle and 3. main spindle.

Usually mechanical transmission elements consist of: belt transmission or combination of belt transmission with gearbox (with two, three or four speeds).

Intensive development of quality tool materials enable using of very high cutting speeds and power.

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Necessary output power on the main spindle can be calculated as:

$$P = \frac{Ft \cdot v}{60 \cdot 10^3} \quad [\text{kW}] \tag{1}$$

where: Ft-tangential cutting force component [N]; v-cutting speed [m/min].

CNC machine tools are used for production of workpieces with different shapes, dimensions and materials, with wide range of cutting data.

For ensuring these requirements the speeds on the main spindle must be regulated in very wide range,

$$Rms = \frac{n_{max}}{n_{min}} = \frac{v_{max}}{v_{min}} \cdot \frac{D_{max}}{D_{min}} = Rv \cdot Rd \tag{2}$$

where: Rms-range of regulation of output main spindle speeds; Rv -range of regulation of cutting speeds; Rd -range of diameters of the parts, or of the cutting tools; $n_{max}$, $n_{min}$ -maximal and minimal main spindle speed; $v_{max}$, $v_{min}$ -maximal and minimal cutting speed; $D_{max}$, $D_{min}$ -maximal and minimal diameters of the parts or the cutting tools.

According to our empirical investigation the range of regulation of main spindle speeds for CNC machine tools usually is within Rms=20-350 (exclusively rare to 600). Such kind of wide regulation of main spindle speeds needs particular attention in selection of variable speed motors and mechanical transmission elements.

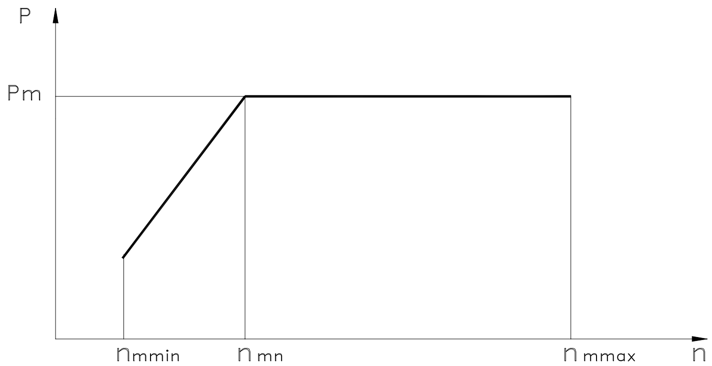


**Fig. 1** Power-speed diagram of variable speed AC motor

Fig. 1 presents power-speed diagram of variable speed motor, where $n_{mmin}$, $n_{mn}$ and $n_{mmax}$ are minimal, nominal and maximal speed of the motor, and Pm is nominal power of the variable speed motor.

Usually range of regulation of speed at constant power of variable speed motors is (2-8) (sometimes reaches values 12-16), which is far bellow required range Rms=20-350.

The overall range of regulation of output main spindle speeds can be calculated as:

$$Rms = Rmsm \cdot Rmsp \tag{3}$$

where: Rmsm=2-50 -range of regulation of main spindle speeds at constant torque; Rmsp=2-45 (exclusively rare 70) -range of regulation of main spindle speeds at constant power.

There are two alternative methods of obtaining wide range of main spindle speeds at constant power: overrating of the AC or DC motor or combining the motor with gearbox with two, three or four speeds.

The second solution with two, three or four speed gearbox is widely used at the CNC machine tools.

Selecting the number of steps Z of the gearbox is in the range of regulation of the variable speed motor with constant power Rmp, while with using the range of variable speed motor with constant torque Rmm=Rmsm, the whole range of regulation of output speeds of the main spindle is obtained [5,2].

Because of that, we can write:

$$Rmsp = Rmp \cdot Rz \tag{4}$$

where: Rmp -range of regulation of variable speed motor with constant power; Rz -range of regulation of the gearbox.

Variable speed motor can be treated as a particular group of gearbox with continuous changing speeds, which is first in the kinematic chain, with infinitely large number of transmissions, with transmission ratios which obtain geometrical progression with progression ratio $\varphi \rightarrow 1$ and range Rmp.

Gearbox can be treated as a transmission group which extend the speed range of the motor at constant power. Because of that characteristic of a transmission group $\varphi_Z$ is:

$$\varphi_z = \mathrm{Rmp} \cdot \varphi \tag{5}$$

Because $\varphi \rightarrow 1$, we obtain

$$\varphi_z = Rmp \tag{6}$$

As,

$$Rz = \varphi_z^{(z-1)} \tag{7}$$

we can write

$$Rz = Rmp^{(z-1)} \tag{8}$$

With the substitution equation (8) in (4), we get

$$\mathrm{Rmsp} = \mathrm{Rmp} \cdot Rmp^{(z-1)} = Rmp^z \tag{9}$$

where: Z-number of speeds of the gearbox.

With known Rmsp and Rmp, using the equation (9), we can calculate the necessary number of speeds of the gearbox ZE:

$$ZE = \frac{log\ Rmsp}{log\ Rmp} \tag{10}$$

The equation (10) is recommended also in the literature [5,2,1,3,4].

Because ZE is usually a decimal number, it is round to the nearest full number.

If Z > ZE we get characteristic with overlapping speeds (fig.2a).

In case Z < ZE we get characteristic with step decrease of the power $\Delta P$ (fig.2b).

For example, if from equation (10) we get ZE=2.5, than Z can be 2 or 3.

In case of Z=3 we get P-n characteristic as in the fig. 2a, and if is accepted Z=2 we obtain characteristic as in the fig. 2b.

Percentual decrease of the power ΔP in relation with the nominal power Pm of the motor, when Z < ZE can be calculated with the equation (11),

$$\frac{\Delta P}{Pm} = \left(1 - Rmp \cdot \sqrt[z-1]{Rmp / Rmsp}\right) 100\ [\%] \tag{11}$$

Usually ΔP/Pm should not be greater than 30% [5,2,1,3,4].

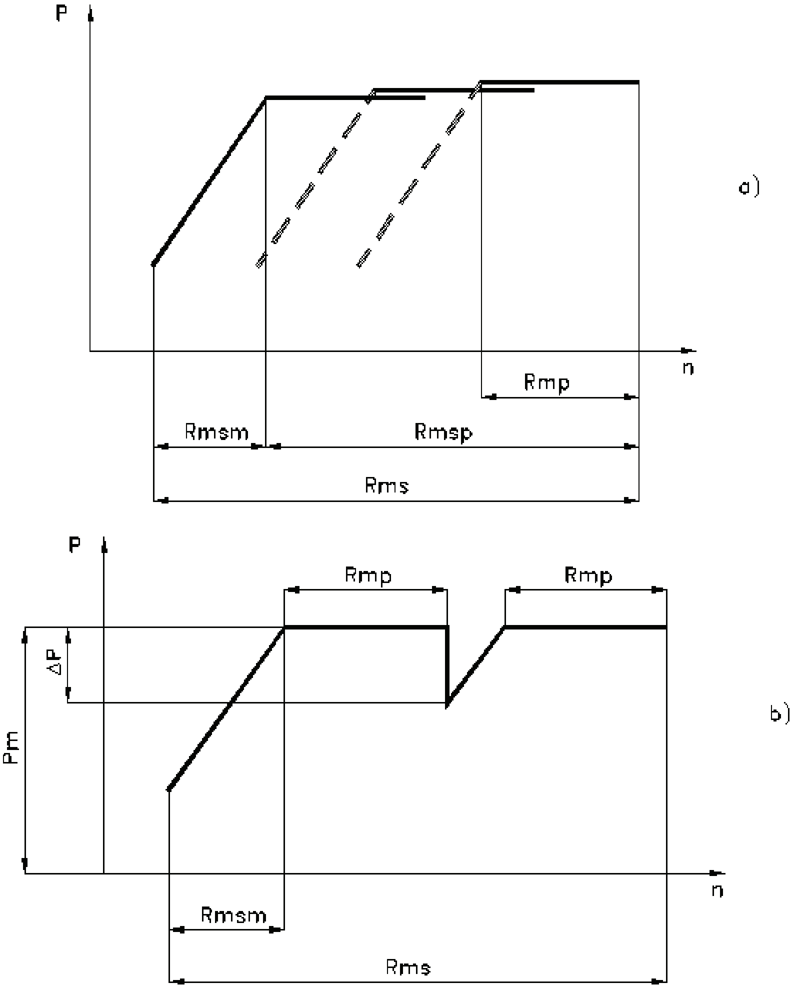


**Fig. 2** Diagram P-n of the main spindle a) with Z=3 and b) with Z=2

## 3 DESCRIPTION OF COMPUTER PROGRAM FOR DESIGNING MAIN SPINDLE DRIVES

Theoretical considerations mentioned in previous chapter are implemented in the computer program. An original computer program for interactive design of main spindle drives and analysis of different design variants was created for PC in C-language.

Flow chart of the computer program is given on fig.3.

The program begins with input of tangential cutting force component Ft and cutting speed v. They are necessary for calculation of required power. Exists a possibility to enter directly required power for particular size of CNC machine tools based on recommendations implemented in the computer program. Recommendations are result of the empirical investigations of main spindle drives of CNC machine tools. More than 2000 different CNC machine tools were investigated and appropriate recommendations were derived.

In the next step the computer program selects variable speed motor from the AC and DC motor database. For the selected motor the program draw power-speed (P-n) diagram and torque-speed (M-n) diagram. The P-n and M-n diagram are shown on fig.4.

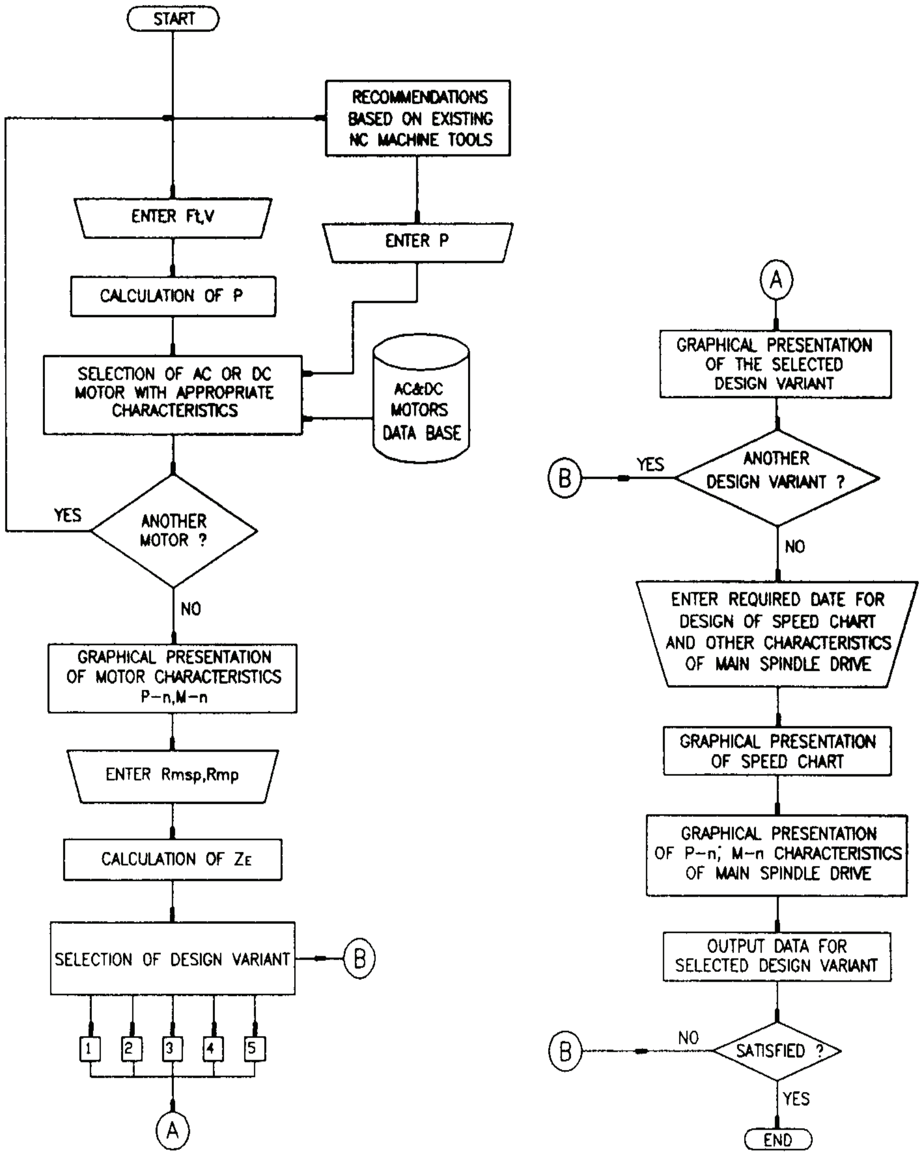


**Fig. 3** Flow-chart of the computer program

The next step requires input of Rmsp-range of regulation of main spindle speeds at constant power and Rmp-range of regulation of the variable speed motor with constant power. This is necessary for calculation of number of speeds of the gearbox ZE.

Then the computer program gives opportunity of selection one of the most usually used design variants of main spindle drives for CNC machine tools: 1. motor-belt-main spindle, 2. motorplanetary gearbox-belt-main spindle, 3. motor-belt-gearbox-main spindle, 4. motor-belt-gearbox-belt-main spindle, 5. motor-belt-reducer-main spindle.

After selection of particular design variant its graphical presentation is shown (fig.5).

In the next step elements for drawing speed chart (transmission ratios in the gearbox, transmission ratio(s) of the belt transmission(s) etc.) are required.

Follows graphical presentation of speed chart (fig.6), power-speed (P-n) and torque-speed (M-n) diagrams (fig.7) and textual presentation of the output data for selected design variant (fig.8).

If we are not satisfied with output data, we can select another design variant.

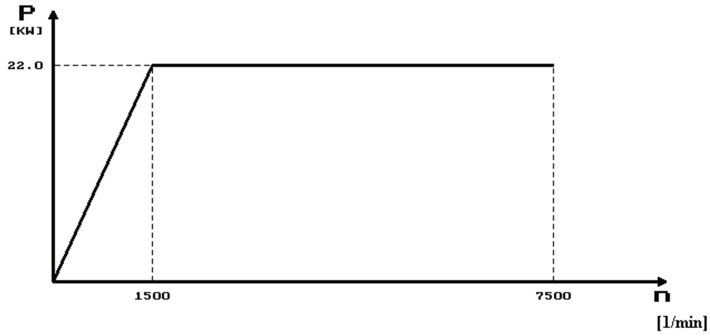



**Fig. 4** P-n and M-n diagram for the selected variable speed motor

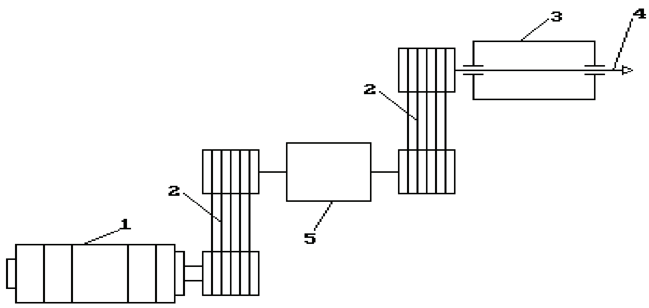


**Fig. 5** Graphical presentation of design variant motor-belt-gearbox-belt-main spindle: 1.variable speed motor, 2.belt transmission, 3.spindle unit, 4.main spindle, 5.gearbox (Z=2,3 or 4)

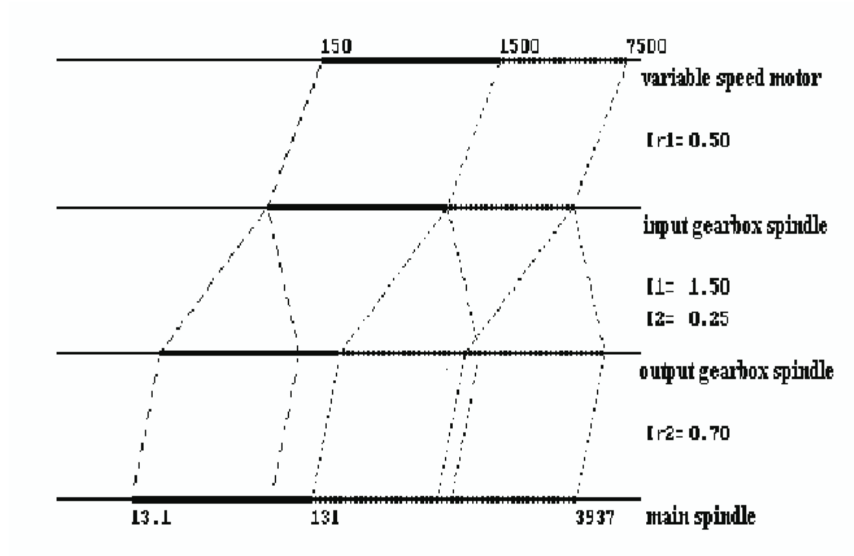


**Fig. 6** Speed chart for the selected design variant motor-belt-gearbox (Z=2)-belt-main spindle

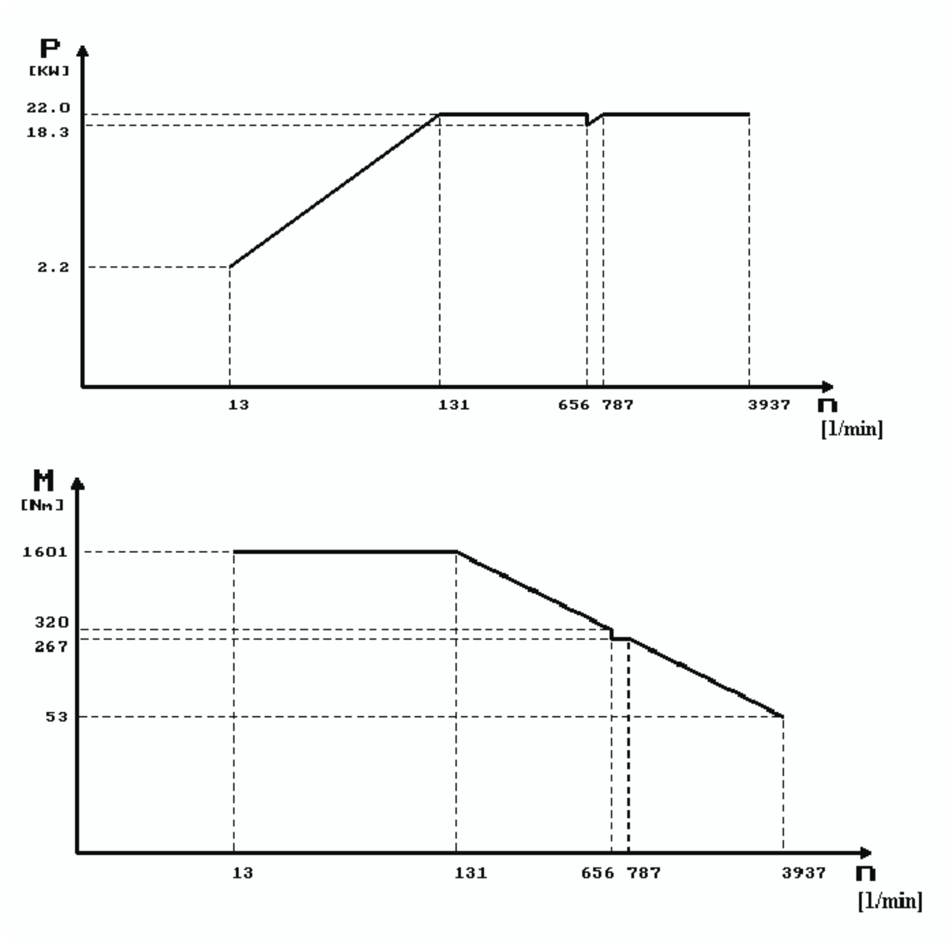


**Fig. 7** P-n and M-n diagram of the main spindle

***OUTPUT DATA FOR SELECTED DESIGN VARIANT***

***motor-belt-gearbox (Z=2)-belt-main spindle***

| | |
|---|---|
| ***Nmin-minimal main spindle speed*** | ***Nmin=13.1 [1/min]*** |
| ***Nmax-maximal main spindle speed*** | ***Nmin=3937 [1/min]*** |
| ***P-maximal main spindle power*** | ***P=22 [KW]*** |
| ***Pmin-minimal main spindle power*** | ***Pmin=2 [KW]*** |
| ***Mmax-maximal main spindle torque*** | ***Mmax=1601 [Nm]*** |
| ***Mmin-minimal main spindle torque*** | ***Mmin=53 [Nm]*** |
| ***Rms-range of regulation of the main spindle*** | ***Rms =300.00*** |
| ***Rmsp-range of regulation of the main spindle at constant power*** | ***Rmsp=30.00*** |
| ***Rmsm-range of regulation of the main spindle at constant torque*** | ***Rmsm=10.00*** |

**Fig. 8** Output data for the main spindle design variant

## 4 CONCLUSIONS

Characteristics of main spindle drives for CNC machine tools directly depend upon skillfulness of composing variable speed motors and mechanical transmission elements.

The presented computer program enables interactive design and analysis of different variants, reduces the design time and modernizes design process of main spindle drives.

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