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ADAPTIVE DESIGN OF SPINDLE MACHINE TOOL

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Abstract: Article describes the development of an application for generating 3D models of bearings used in the design of machine tool spindles. The models are created in CATIA v5 software using parametric modelling, which allows for easy modification of bearing dimensions and types according to the selected type from the database. The application has two main parts: spindle design and the generation of bearings. In the future, we plan to develop other headstock components such as spindle front ends, seals, clamping and other elements in this way. The user interface is simple and designed for fast work. The software has a modular structure and can be easily expanded and modified.

KEYWORDS: bearing, spindle, 3D model, machine tool

1 Introduction

Quality of the machine tool depends mainly on the quality of the spindle, as shown in Figure 1. Machine spindles are a key component of machine tools, and their design is a complex task that is difficult to solve without the use of powerful computing technology and suitable software. For its solution, designers must analyse and consider several factors that affect the functioning of the entire bearing, including mechanical and material properties spindles and other components as well as its dynamic behaviour, [6], [7].

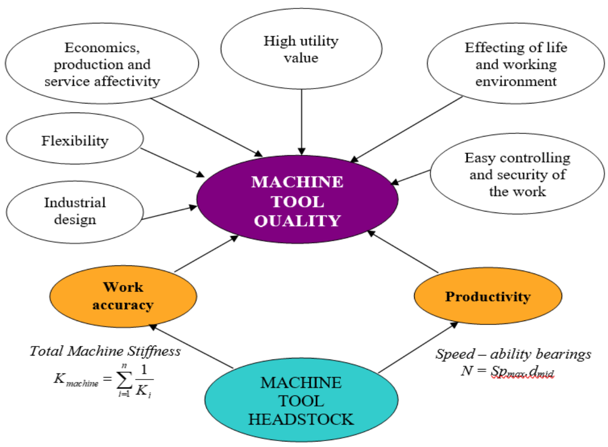

Fig. 1 Factors influence on Quality of Machine Tool

The aim of this article is to create an application that will enable the quasi-automated design of a machine tool spindle. This article will also mention parametric modelling and its integration into the proposed application, with the capability of generating spindle design parts. Spindles are mainly manufactured in two designs, box-shaped and tube-shaped, as can be seen in Figure 2.

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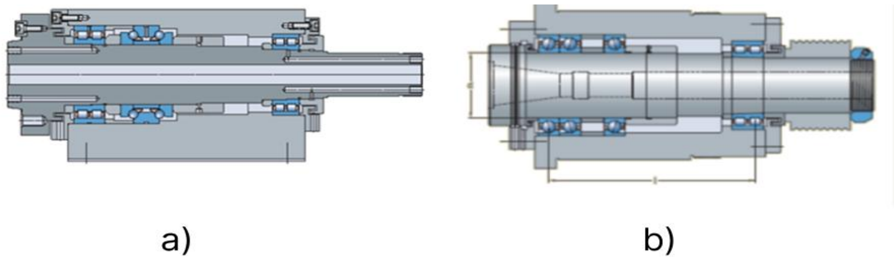

Fig. 2 a) Box-shaped spindle b) Tube-shaped spindle

2 Software for spindle design

Main purpose of this application is to offer designers a user interface for spindle design and analysis. Various parameters that need to be taken into account when designing spindles are considered. The application is divided into two modules, “Spindle Design and Calculation” and “Spindle Part Generation”.

Both modules are shown together in Figure 3.

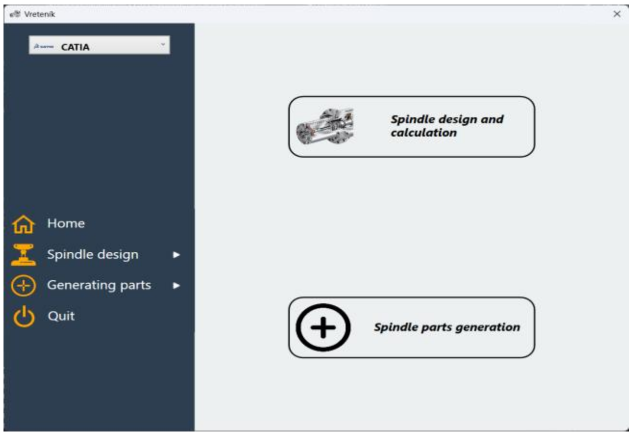

Fig. 2 User interface of application

First module provides several sub-modules which allows you to define and change its geometric parameters such as diameters, lengths, material and other aspects that need to be considered when designing a spindle of a machine tool. Different elements (sub-modules) of this module can be seen in Figure 4.

Sub-modules mentioned above allow gradual selection and setting of key parameters of the spindle. First, a preliminary design with the type and basic concept of the spindle is defined. Then, depending on the type of machine tool, the user selects the front clamping part of the spindle.

The focus of the third step is on selecting bearings and their dimensions from a prepared database. The application provides access to starting parametric models of rolling bearings used in spindle design. Flowchart of communication between the user and the application is shown on Figure 5.

Following the same principle shown on Figure 5, it is possible to generate the structural parts of the headstock as well as the spindle itself, the clamping elements, the gasket, and more... The geometry of the entire model can be controlled using a modelling method called parametric modelling, where the created parameters directly control the dimensions and geometry of the component [1], [2].

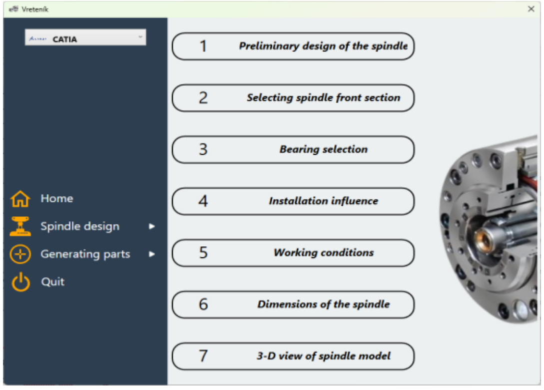

Fig. 4 Sub-module for spindle design

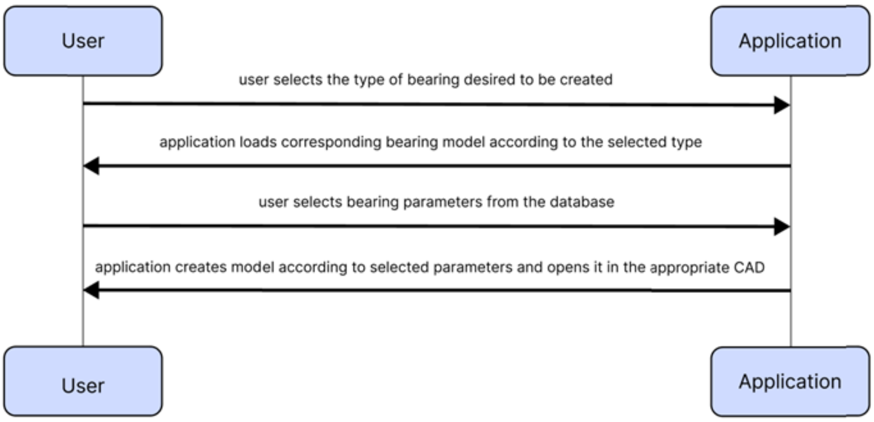

Fig. 5 Sequential diagram showing a 3D model of the bearing created by the software

The application was used to create starting rolling bearings used in the construction of machine tool spindles. On Figure 4, we can see a cross-section of a radial ball bearing with the main parameters of the bearing highlighted. These main parameters are the same for all types of bearings:

- Inner diameter (d)
- Outer diameter (D)
- Width (B)
- Curvature Radius (R)

On Figure 7, you can see the tree structure of the radial ball bearing, where you can see a separate section called "Parameters." Within the individual components, these parameters are only found as a reference to the parameter from the main assembly – for this reason, the parameters are marked as "External Parameters". A change in the value of one parameter of the main assembly will be reflected throughout the entire assembly wherever this parameter was included.

3 Design of the spindle dimensions according to the superposition method

To calculate the spindle front deflection, optimal bearing distance, and overall stiffness of the spindle-bearing system according to [3], each method offering certain advantages but also having its limitations. In our software, we use the superposition method to define the basic dimensions of the spindle.

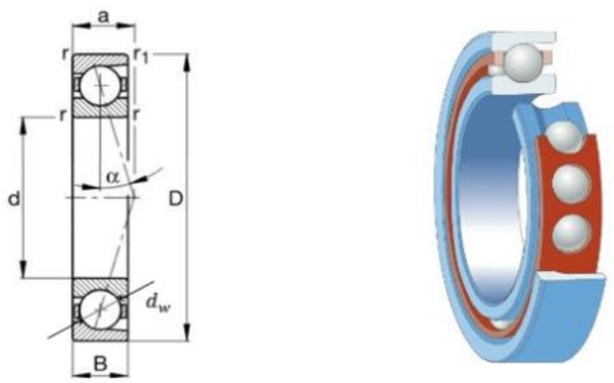

Fig. 6 Main parameters cross-section of a single - direction radial ball bearing with angular contact [5]

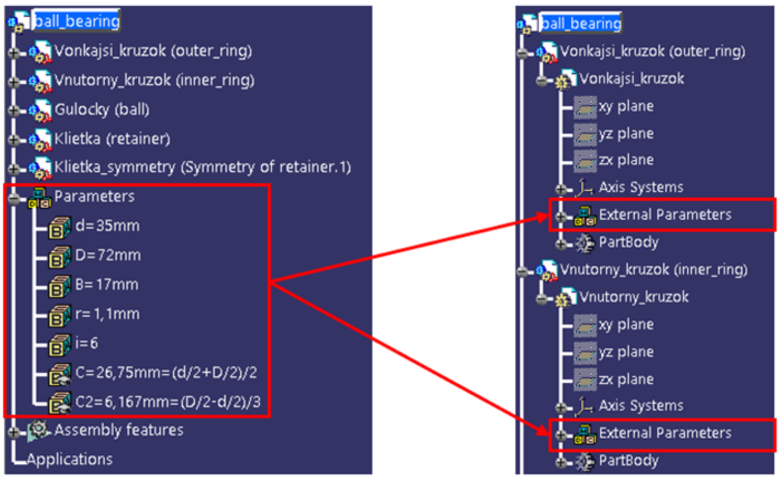

Fig. 7 Parameters from the main document linked within individual parts within assembly

According to this method, the resulting deformations are directly proportional to the load acting on the spindle. The total deflection of the spindle is determined as the sum of the individual loads acting separately. It consists of two main components, which are:

1. Deflection of the front end of the spindle due to bending moments (y_v), caused by the deflection of the spindle itself from the bending load of the radial force F_r acting on the front end of the spindle at the point of contact between the tool and the workpiece.
2. Displacement of the front end of the spindle caused by bearing flexibility (y_L) – caused by radial force F_r.

On Figure 8, there's a diagram of the spindle with the basic parameters we'll use in our calculations, which are also listed in equations (1) – (4).

Equation that we have implemented in the computational part of the application is taken from [3] and states that the total deflection y_c is given by the sum of both of the above components (y_v a y_L).

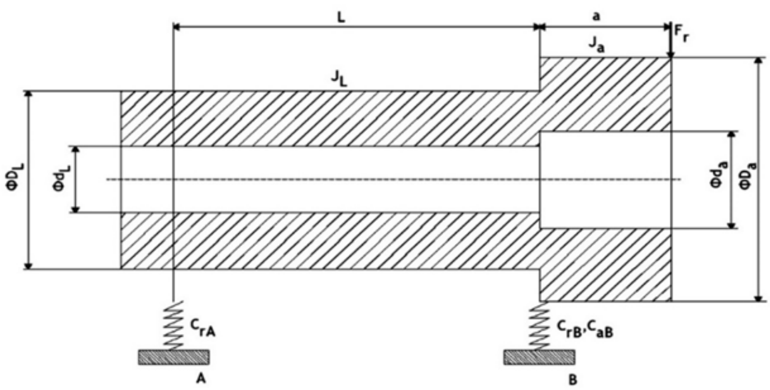

Fig. 8 Spindle schematic diagram [4], [5]

$$y_c = y_v + y_L = \frac{F_r \, . \, a^2}{3 \, . \, E} \, . \left[\frac{L}{J_L} + \frac{a}{J_A}\right] + \frac{F_r}{L^2} \, . \left[\frac{a^2}{C_A} + \frac{[L+a]^2}{C_B}\right] \tag{1}$$

Text Quadratic moments of both bearing nodes (J_L, J_A) are calculated according to the following equation for calculating quadratic moments:

$$J_x = \frac{\pi}{64} \, . \, [D^4 - d^4] \tag{2}$$

The stiffness of bearing nodes A and B is selected in a separate window "Select support", which can also be found in Figure 9. To calculate the radial stiffness, we use the following equation according to [3]:

$$C_{rz} = \frac{3 \, . \, 10^{-3}}{4} \, . \, z^{2/3} \, . \, k_\delta^{2/3} \, . \, i_1^{2/3} \, . \, F_p^{1/3} \, . \, \frac{[\cos \alpha]^2}{[\sin \alpha]^{1/3}} \, . \left[1 + \frac{i_2^{2/3}}{i_1^{2/3}}\right] \tag{3}$$

Coefficient k_δ depends on the type of bearing and its rolling element. Based on the type of bearing, according to [3], the coefficient is calculated according to Table 1.

Table 1. Forms for calculating the k_δ coefficient for different types of rolling elements [3]

Type of rolling element	**Roller**	**Ball**	**Taper**
k_δ	$2680 \, . \, l_w^{0,92}$	$10^5 \, . \sqrt{1{,}25 \, . \, d_w}$	$7{,}67 \, . \, 10^4 . \, l_w^{0,665}$

Preload force is determined according to the relationship resulting from the ČSN 02 4615 standard, which is determined according to the following equation:

$$F_p = k \, . \, C_r \, . \, 10^{-2} \tag{4}$$

Value of the axial coefficient „k“ changes according to the amount of preload (low, medium, large). This coefficient changes according to the contact angle and its value is defined by the ČSN 02 4615 standard. Quantities contained in equations (1), (2), (3), and (4) are described in more detail in the „List of physical quantities and symbols“.

3.1 Characteristics affecting overall spindle deflection

3.1.1 Deflection of the spindle due to bending moments (y_v)

When radial force F_r is applied, spindle deflects like a cantilever, with the greatest deflection occurring at the front free end of the spindle. Contribution to the total deflection the contribution to the total deflection of the spindle front end from bending moments depends mainly on the spindle material, which is characterized by Young's modulus of elasticity (E) and by the geometry of the spindle (J_A, J_L).

Young's modulus of elasticity (E): The stiffer material (higher E), the smaller the deflection (e.g. steel $E \approx 210$ GPa compared to Aluminium, which has $E \approx 70$ GPa)

Moments of inertia (J_A,J_L): Depends on the outer and inner diameters of the spindle within individual sections.

3.1.2 Displacement of the front end of the spindle due to bearing compliance (y_L)

Bearings are not perfectly rigid – when radial force (F_r) is applied, they shift slightly. This effect is particularly significant at high loads. The shift is directly proportional to the force and inversely proportional to the rigidity of the bearing assembly.

Stiffness of bearing nodes (Cr_A,C_{rB}): For spindle arrangement, rolling bearings are mostly used (more than 90%). The deflection due to bearing flexibility decreases with higher stiffness of bearing nodes.

Layout of bearings (length dimensions „a“ and „L“):

Total spindle deflection is also affected by the length parameters „a“ a „L“, where „a“ represents the distance of the radial force (F_r) is applied and „L“ parameter represents the distance between bearing nodes A and B.

4 Sub – module for optimal spindle length calculation

As part of the spindle calculation software, a specialized sub-module was created to calculate the optimal spindle length between the supports based on specified operating and design parameters. The basis for calculating the optimal length is equation (1), which was described in the previous subsection. Module allows you to examine the deflection curve along the spindle length interval depending on various combinations of radial and axial forces, drive influence, geometric and material properties. User interface is shown on Figure 9.

Results are visualized as a graph of total deflection of front end of spindle and its components depending on spindle length. Thus, the user can quickly assess at what spindle length between supports we achieve minimum total spindle deflection y_c and thus maximum stiffness of the spindle-bearing system. Plots of the individual components together with the optimal length can be seen in Figure 10.

Part of the module is the ability to assess and check the achievement of the required spindle stiffness value, marked with a green curve shown in Figure 11.

Green curve represents stiffness behaviour of spindle depending on its length in the range from 100 mm to 700 mm. Based on the entered input data, this module calculates how the total stiffness of the spindle-bearing system changes at different spindle lengths.

Below the graph, there is also a brief interpretation of the results shown in the graph. It provides information on the range in which the required stiffness was achieved.).

Table 2. List of physical quantities and symbols

Designation	Unit	Meaning
y_c	[mm]	Total spindle front end deflection
y_v	[mm]	Deflection of the spindle due to bending moments
y_L	[mm]	Spindle front end deflection due to bearing compliance
F_r	[N]	Radial force
Designation	**Unit**	**Meaning**

a	[mm]	Distance of force action from node A
L	[mm]	Distance between bearing nodes
E	$[GP_a]$	Young's modulus of elasticity
J_x	$[kg\,.mm^4]$	Quadratic moment
C_x	$[N.mm^{-1}]$	Radial stiffness of the bearing node
z	$[-]$	Number of rolling elements
k_δ	$[-]$	Coefficient for radial stiffness calculation
i_x	$[-]$	Number of bearings in bearing node
F_p	$[N]$	Preload force
α	[°]	Contact angle of bearing
C_r	$[N]$	Dynamic load capacity of the bearing
k	$[-]$	Constant according to ČSN 02 4615 standard
D	$[mm]$	Outer diameter
d	$[mm]$	Inner diameter
l_w	$[mm]$	Rolling element length
d_w	$[mm]$	Rolling element diameter

Fig. 9 User interface for designing the optimal spindle length

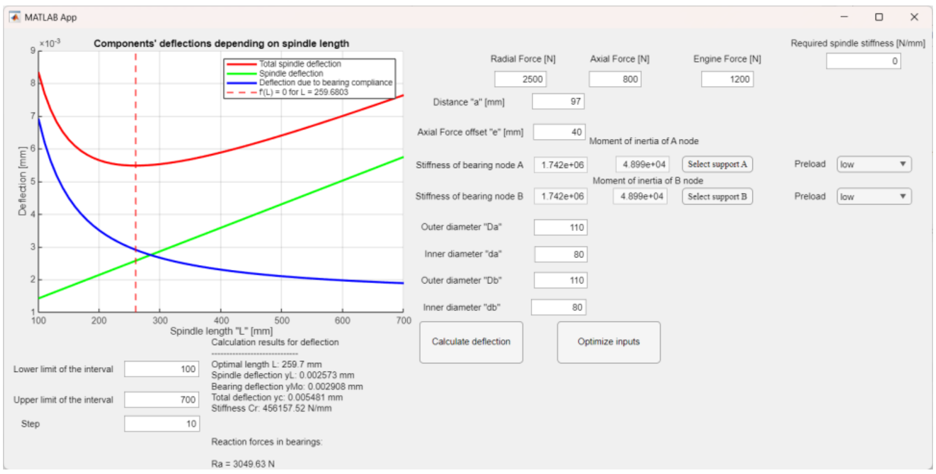

Fig. 10 Calculation of optimal length of spindle

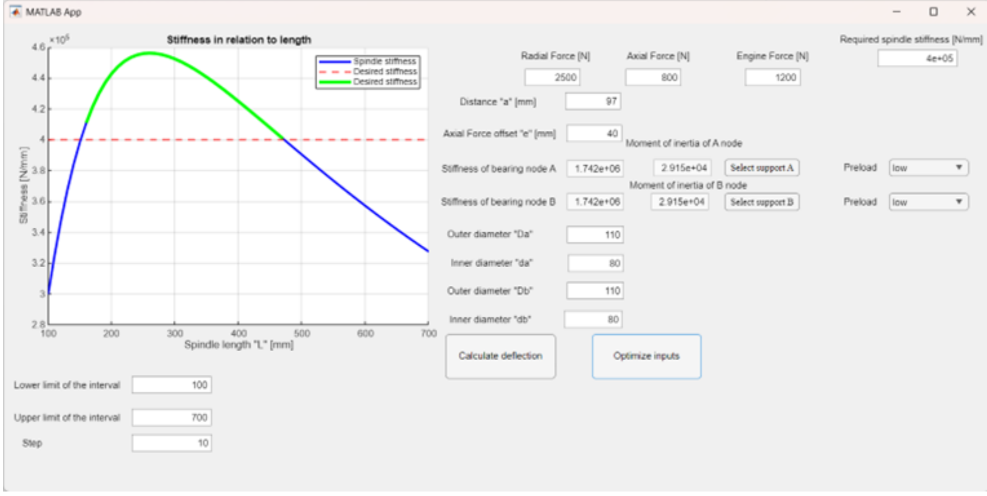

Fig. 11 Achieving the required spindle stiffness

CONCLUSION

Aim of the submitted paper was to present the state of development of a specialized software system for fast and efficient design of the spindle-bearing system. The software architecture is modular, and additional modules are currently being developed with the aim of achieving the final state – comprehensive application software for the design and optimization of machine tool headstock.

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