Contribution to the research of static and dynamic properties of CNC turning machine

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Spindle headstock (SH) of the machine tools plays a major role in the fulfilling the required working accuracy and productivity. Radial ball bearings with angular contact are still more and more applied in an arrangement. The spindle-housing system (SHS) complex analysis is very difficult and complicated. The analysis requires deep knowledge of mathematics, mechanics, machine parts, elastohydrodynamic theory, rolling housing technique and also programming skills. Software package (SW) – Spindle Headstock, Rel. 2.8 – carried out at the Department of Production Engineering has been applied for designing of the precise accuracy running spindle onto the lathe SBL 500 CNC.

Key words: headstock, spindle-housing system, ball bearings with angular contact, machine tools, lathe, static analysis, dynamic analysis, mathematical models, accuracy, productivity

1. Introduction

The quality, quantity and effectiveness of enhancing the production volume are considerably depending on technical and technological parameters of machine tools. The headstock plays the most important role in force flow of a machine tool with principal rotating motion.

The headstock like the tool or workpiece carrier has a direct relationship to static and dynamic properties of the cutting process. The spindle-housing system (SHS) stiffness has influence on surface quality, profile and dimension accuracy of production parts. It also has direct relationship to machine tool productivity, because the ultimate cut width characterized by initialization of self-exciting vibration is directly proportional to machine tool stiffness and damping.

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The SHS complex analysis is very difficult and complicated. The analysis requires deep knowledge of mathematics, mechanics, machine parts, elastohydrodynamic theory, rolling housing technique and also programming skills.

2. Theoretical research

The main goal of theoretical research is to gain information about headstock working conditions loaded by forces, which with their values and configuration are modelling real cutting forces. Creation of the mathematical models, which suitably define the SHS static and dynamic characteristics, was affected in the past by the level of computing techniques. The most realistic consideration of the given housing already in the construction design phase has an increasing importance in present time. This will be reflected both in the design quality and in economical cost of developing the new machine. These are the reasons why a need arose to analyse mathematical models which can describe SHS working properties as realistically as possible. The parameters, which are not in the known models or which are taken into consideration only partially, are implemented in the calculation process.

In the created mathematical models creating, modular architecture (Fig. 1) is applied. It enables us to independently create mathematical models relating to:

- *single mounting elements* – bearing nodes, spindle noses, clamping elements, supporting elements,
- *complete spindle-housing system* – stiffness, durability, running accuracy.

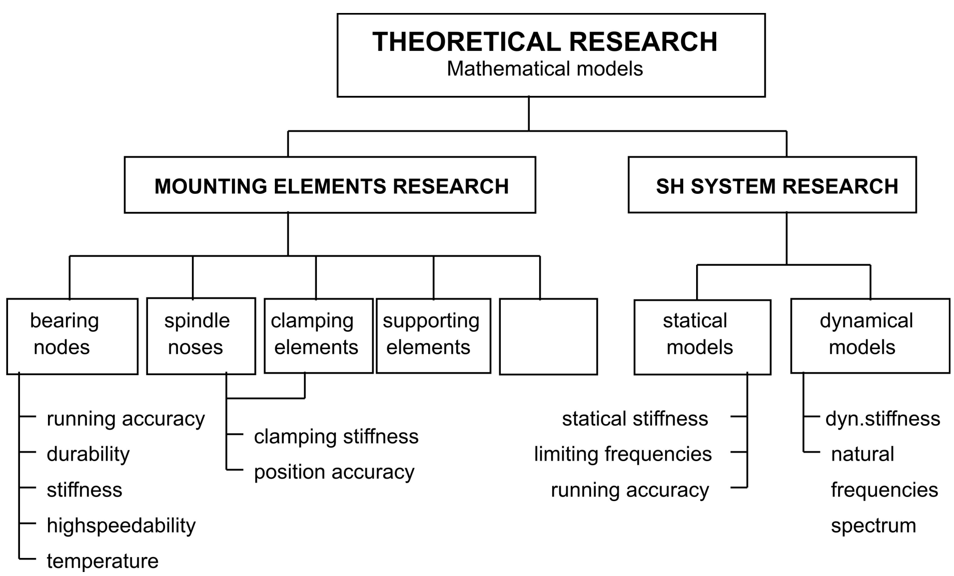

Fig. 1. Modular structure of theoretical research.

2.1. Static analysis

The static analysis describes the motionless spindle ($n = 0$ min^{-1}) and the spindle with constant loading forces. Many static mathematical models were created and factors which are usually taken into analysis are contained in Eq. (1).

The resulting static deflection of the front-end spindle can be explicitly described [1] by multiparametrical equation in shape:

$$y_{\mathrm{F}} = f[E, F_{\mathrm{r}}, F_{\mathrm{a}}, F_{\mathrm{Z1}}(F_{\mathrm{Z2}}), a, L, (b \ldots), \rho, C_{\mathrm{B}}, C_{\mathrm{A}}, D1, V1, D2, V2] \tag{1}$$

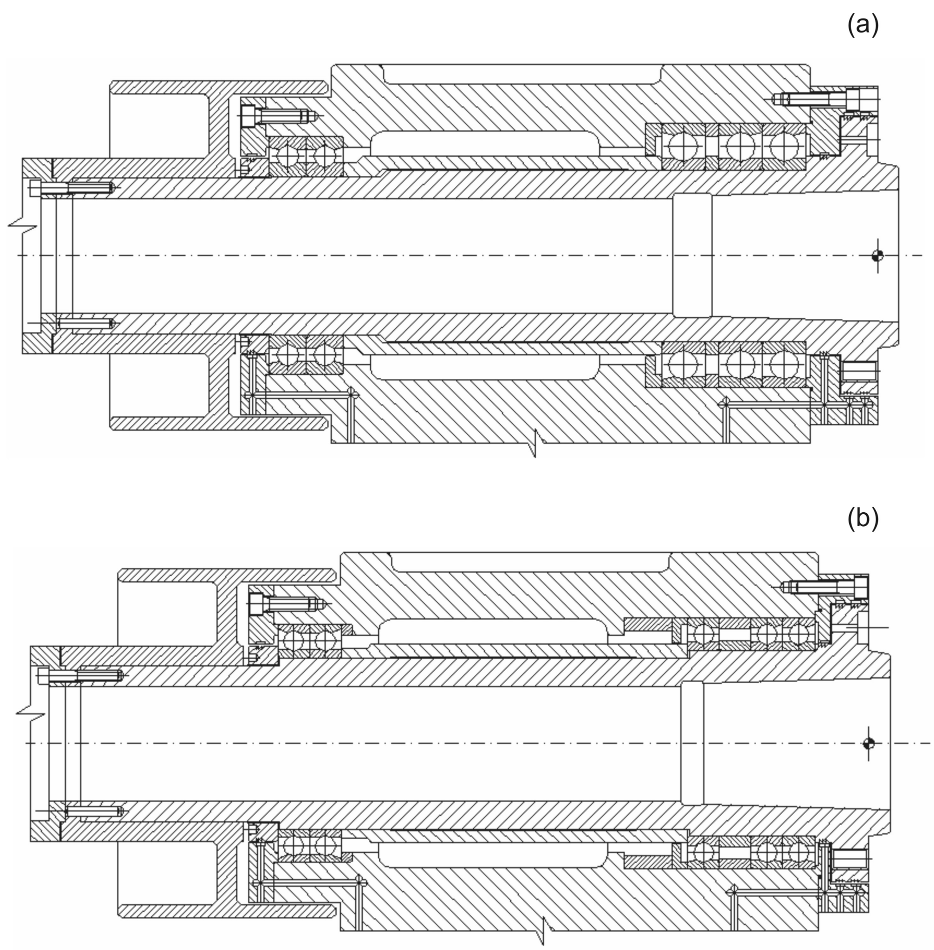

Fig. 2. Headstock of SBL 500: (a) original design, (b) optimized design.

and depends especially on:

– spindle material and dimensions (E, $D1$, $D2$, $V1$, $V2$),
– loading forces position, orientation and magnitude (F_{r}, F_{a}, F_{Z1}, (F_{Z2}), r_{F}, b),
– bearing arrangement configuration and stiffness (C_{A}, C_{B}),
– spindle and bearing arrangement space configuration (L, a),
– spindle box construction ...

The resulting static deflection of the front-end spindle:

$$y_{\mathrm{r}} = y_{\mathrm{Mo}} + y_{\mathrm{L}} + y_{\mathrm{t}} + y_{\mathrm{Fa}} \qquad [\mu\mathrm{m}] \tag{2}$$

is superposition of deflections from:

– bending moments (y_{Mo}),
– bearing stiffness (y_{L}),
– transversal forces (y_{t}),
– axial force (y_{Fa}).

Then radial stiffness and axial stiffness SHS equal

$$C_{\mathrm{r}} = \frac{F_{\mathrm{r}}}{y_{\mathrm{r}}}, \qquad C_{\mathrm{a}} = \frac{F_{\mathrm{a}}}{y_{\mathrm{a}}} \qquad [\mathrm{N}\ \mu\mathrm{m}^{-1}]. \tag{3}$$

The method of initial parameters in matrix shape – the method of transfer matrix was applied in the mathematical model [3] created for the calculation of static parameters. The main advantage of this method in computer form (Headstock V 2.8) is the possibility to repeat single calculating algorithms in matrix form.

The TRENS, a. s., Trenčín as a Slovak manufacturer of machine tools, mainly lathes, offers a new generation of lathes incorporating a number of technological

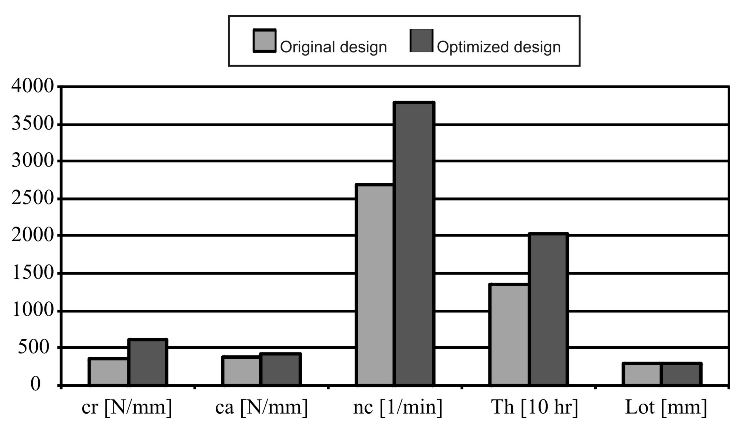

Fig. 3. Graphical comparison of calculated values.

advances in design, production and control systems. The Department of Production Engineering has applied the design of the precise accuracy running spindle onto the lathe SBL 500 CNC (Fig. 2a). All construction data and results of measurements were obtained from the producer. Table 1 shows calculated (Headstock Version 2.8) values of original construction.

Optimized construction of spindle-housing system is shown on Fig. 2b. On Fig. 3 is graphical comparison of calculated values for original and optimized construction of spindle-housing system SBL 500.

Table 1. Calculated values of original construction of spindle–housing system

	Unit	Value	Notice [%]
Total radial stiffness C_{r}	[N μm^{-1}]	351	
Total axial stiffness C_{a}	[N μm^{-1}]	372	
Total spindle displacement y_{r} consists of	[μm]	18.45	
– the bending moments y_{Mo}	[μm]	9.79	53.0
– the bearing compliance y_{L}	[μm]	6.16	33.5
– the cross-acting y_{t}	[μm]	2.49	13.5
Limited frequency of rotation n_{c}	[min^{-1}]	2695	unfit
Life-time T_{h}	[hour]	5175	unfit
Distance between supports L_{ot}	[mm]	327	

2.2. Dynamic analysis

While the static analysis of the *spindle-housing system* describes the spindle behaviour in a rest state, the dynamic analysis describes the spindle in real operation and so the real state is represented better. It is very important to know the dynamic characteristic, especially at high-speed headstocks [5]. It must be ensured that working revolving frequencies are not in the resonant zone. In that case the vibration amplitude of the spindle could be considerably increased and spindle total stiffness would decrease to unsuitable values.

The most frequent determining dynamic characteristics of SHS are:

– the spectrum of natural (resonant) frequencies (usually the first three frequencies),

– amplitudes of vibrations along the spindle in dependence on revolving frequencies of the spindle,

– resonant amplitudes of vibrations,

– dynamic stiffness of the spindle (at given revolving frequency of the spindle).

The SHS dynamic properties (dynamic deflection of spindle front-end, natural frequencies spectrum) [2] are affected by the factors shown in Fig. 4.

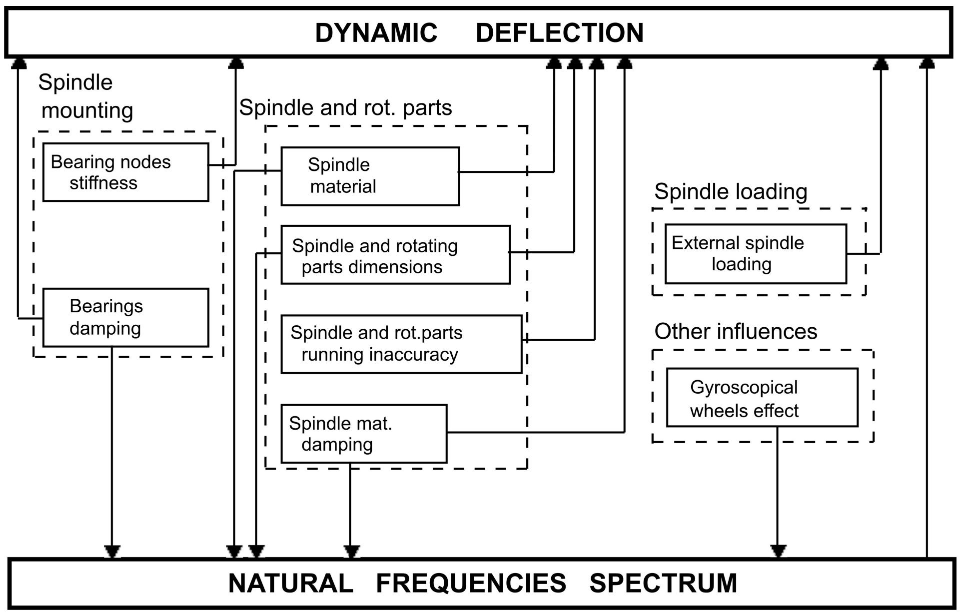

Fig. 4. Factors affecting SHS dynamic properties.

2.3. Mathematical models for determining spindle dynamic properties

Nowadays, the only reliable way to discover dynamic properties is experimental measurement and therefore creation of reliable mathematical models for determining SHS dynamic properties is very useful.

In compliance with spindle mass reduction, mathematical models are divided into:

1. discrete models with 1°, 2° and $N°$ degrees of freedom,
2. continuous models.

The discrete mathematical model based on the revolving vibration of spindles with $N°$ degrees of freedom is worked out in [2, 4]. This mathematical model for spindle dynamic properties calculation enables us to take into consideration the effects from rotating part materials and dimensions, bearing arrangements stiffness and radial forces from the cutting process and the effect of the drive. The calculated results are a spectrum of natural frequencies and dynamic deflection of the spindle under discrete masses.

The deflection of spindle y_i loaded by concentrated forces in i-th point can be expressed in the form

$$y_i = a_{i1}F_{1\text{o}} + a_{i2}F_{2\text{o}} + \ldots + a_{ik}F_{k\text{o}} + \ldots + a_{in}F_{n\text{o}} \qquad [m], \tag{4}$$

where a_{ik} [m N^{-1}] is Maxwell's effecting factor and every mass is acting on the spindle by centrifugal force

$$F_{io} = m_i y_i \omega^2 \qquad [N], \tag{5}$$

where m_i [kg] is mass of i-th discrete segment.

The application of given equations and their modifying for n masses will create a system of homogeneous algebraic equations. Solutions of the determinant of this equation system are represented by angular natural frequencies of transversal vibrations of the spindle ω_i [rad s^{-1}].

The calculating procedure for determining dynamic deflections y_i, if the spindle and rotating parts dimensions, bearing arrangements stiffness and radial external forces are considered, is very similar to the previous one. These calculating procedures are described in [2].

$$\Delta = \begin{vmatrix} 1 - a_{11}m_1\omega^2 & -a_{12}m_2\omega^2 & \dots & -a_{1n}m_n\omega^2 \\ -a_{21}m_1\omega^2 & 1 - a_{22}m_2\omega^2 & \dots & -a_{2n}m_n\omega^2 \\ \dots & \dots & \dots & \dots \\ -a_{n1}m_1\omega^2 & -a_{n2}m_2\omega^2 & \dots & 1 - a_{nn}m_n\omega^2 \end{vmatrix} = 0. \tag{6}$$

It is quite easy to transform this mathematical model to computer-comprehensive form, and calculation of the dynamic characteristics is fast.

The most valuable element is the possibility to calculate dynamic stiffness at individual revolving frequencies of the spindle. The presented mathematical model was verified on a number of spindles with programs which make it possible to calculate natural frequencies (COSMOS) and results were in good compliance.

The verified spindle in compliance with [4] was reduced to a three-mass discrete system. The dynamic mathematical model described above was used for natural frequencies and dynamic deflections calculations. Table 2 gives comparison of calculated and experimental values.

Table 2. Experimental and calculated values of frequencies

Frequency	Calculated	Experimental	Difference
$f1$ [Hz]	1 201	940	+27.8 %
$f2$ [Hz]	1 727	1610	+7.3 %
$f3$ [Hz]	10 605	–	–

The results can be considered as correct, in spite of relatively large difference of values (28 %) at the first frequency. This is caused by the fact that the dimensions of supplementary rotating parts were not at disposal. If these parts are taken into consideration, the values of theoretical natural frequencies will drop down.

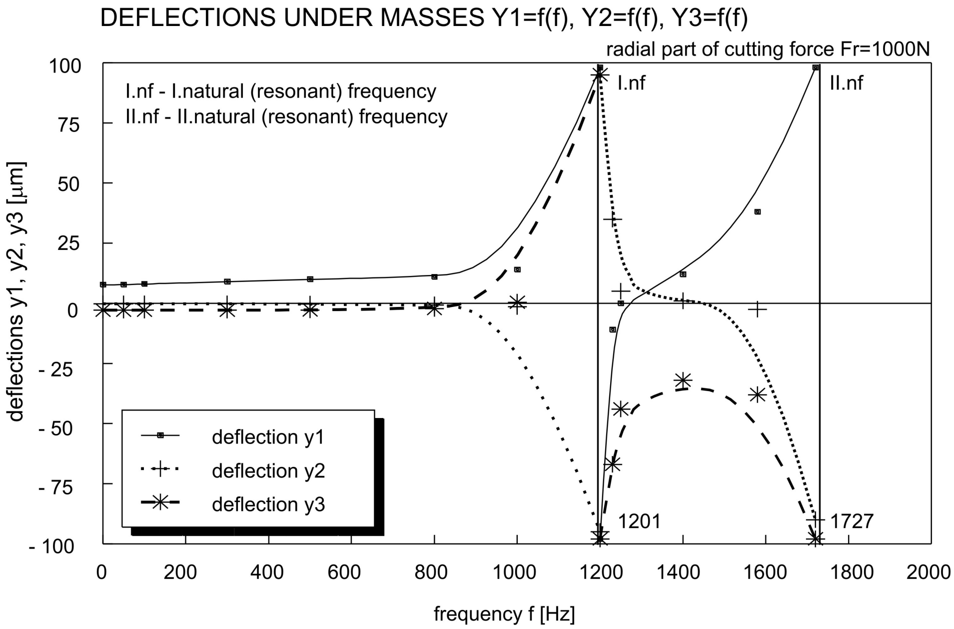

Fig. 5. Dynamic deflections of the spindle in compliance with [4].

The example of graphic output of calculated values is in Fig. 5. The chart shows dynamic deflection of the spindle reduced to three masses, in dependence on the revolving frequency under separated masses. The first two resonant frequencies of the tested spindle are marked in the chart.

3. Conclusion

One of main demands in designing a new spindle-housing system design is the possibility of quick application in practice. The created methodologies of calculation must be verified and the models must be digitalized to a suitable user form. These models must really illustrate characteristics of spindle-housing system.

The calculated results of the mentioned application program (Headstock Version 2.8) were verified with real results of headstocks CNC Lathe SBL 500 (Fig. 6), fy TOS Trenčín and TOS Kuřim.

The difference between measured and calculated values is relatively small.

The convergence of measured and calculated values gives good presumptions for wider application of created programme product in practice.

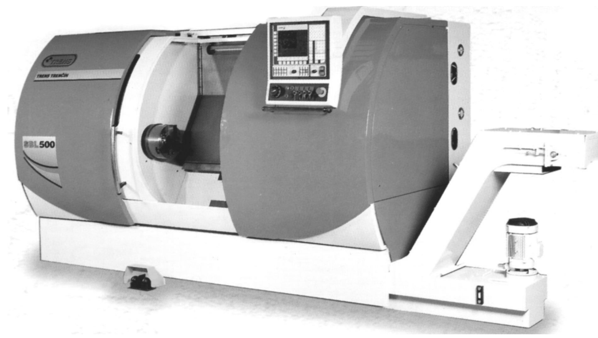

Fig. 6. CNC Lathe SBL 500.

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