

MODELLING AND COMPUTATIONAL ANALYSIS OF SPINDLES IN COMSOL SYSTEM

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Abstract: *This paper presents the opportunities of COMSOL multiphysics computer system for computation analysis of machine tool spindles. The method of modelling of spindle geometry and load from cutting forces and bearing support was presented. Modelling of a workpiece holder with the workpiece was also discussed. With the example of the model of spindle assembly in a medium-size lathe, the computational analysis within static and dynamic range was carried out. The deformations of the spindle and the values of displacement at the location of the cutting point were found. Three first frequencies of free vibrations and the corresponding forms of vibrations were also determined. The study confirmed the usefulness of the COMSOL computer software for effective computational analysis for machine tool spindles.*

Key words: *machine tool, spindle, Comsol system, modelling, analysis*



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1. Introduction

Machine tool spindles are the basic constructional component in the machine tools with the main motion being rotation. The spindles perform the following functions in the system of the machine tool (Honczarenko, 2009):

- positioning and fixing a workpiece or a tool in a particular working position;
- generating rotational motion or combined rotational and translational motion (feed) of a workpiece or a tool;
- carrying transverse and longitudinal forces and torques which occur during cutting.

In order to meet these tasks, spindles must be characterized by enhanced rigidity. The rigidity is a fundamental condition which determines spindle dimensions, distance between bearings and selected methods of bearing mounting. Among other requirements imposed on the spindles, one should emphasize:

- high precision of rotation defined by the permissible levels of radial and axial run-out in the rotation axis and the front face;
- resistance to generation of vibrations achieved through symmetrical distribution of rotational masses with respect to the rotation axis, balancing the spindle with all the fixed components;
- resistance of sliding surfaces and retention surfaces to wear and damage.

New designs of spindles used in machine tools are required to show high rigidity of mechanical characteristics, which is a function of rotational speed of motor shaft and the torque on the spindle. Possibility of stepless adjustment of rotational speed up to 50,000 rpm is also essential. Spindles are increasingly often required to operate as control axis C with an option of angular positioning.

Drive systems of spindles are electromechanical drives with direct current motors and stepless gear or drives with asynchronous or synchronous alternate current motors.

Due to the tendencies to use higher cutting speeds, the main drives in CNC machine tools increasingly often feature electro-spindles (Fig. 1). They are the modified designs of asynchronous or synchronous electrical motors, integrated with a spindle.

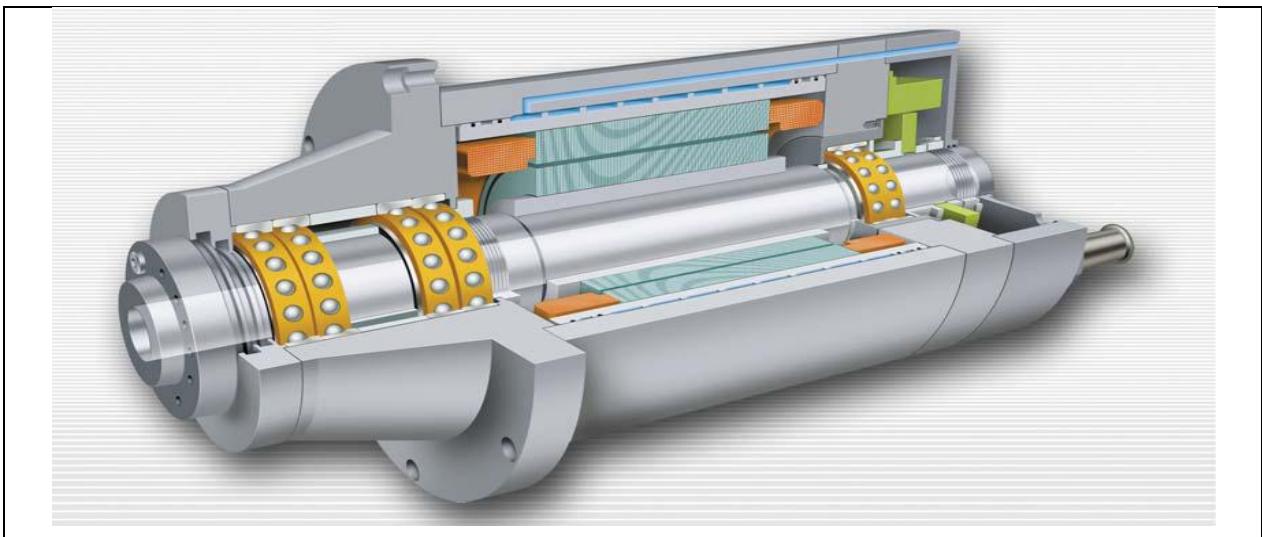


Fig. 1 High-speed electro-spindle manufactured by UKF (***, 2009)

An essential factor which determines the quality of the main drive is bearing mounting. This is typically solved by using rolling-element bearings, sometimes with hybrid arrangement (i.e. with ceramic rolling elements), although recent years have also seen the designs with magnetic bearings. Suitable bearing mounting allows for reaching higher rotational speeds, assuring thermal stability at the same time.

2. Spindle and Electro-Spindle Bearing Mounting

Rolling-element bearing solutions are the most popular designs of bearing mounting. The advantages of rolling-element bearings include (Honczarenko, 2009):

- low motion resistance, easiness of lubrication and assembly;
- operation within a broad range of rotational speeds;
- opportunity of checking clearance and using pretension;
- high carrying capacity and rigidity (cylindrical rollers) and even greater precision;
- normalization of dimensions and serial manufacturing in specialized plants.

Disadvantages of rolling-element bearings include: low ability to absorb vibrations (noise) and high lateral dimensions (except for needle-roller bearings). Rolling-element spindle bearings are manufactured with higher precision class (P) compared to typical commercial bearings.

Using pretension in bearings increases the rigidity of the spindle system. Differences in diameters of rolling elements might be eliminated through using insignificant initial elastic strain. Pretensioning ensures the enhanced resistance to vibrations. The level of pretension is defined according to the rotational speed, load and precision of the roll neck and the hole in the bearing seat. The pretension should be chosen so that, with full load and maximal rotational speed, forces acting on the spindle do not cause a renewed bearing clearance.

Modern designs of spindle bearings include hybrid ball bearings with steel races and ceramic rolling elements.

These bearings are characterized by the following properties (Habrat, 2007):

- four to six times higher life compared to standard precision spindle bearings;
- spindle can be accelerated and decelerated within a range broader than in the case of conventional bearings;
- they allow for reaching very high speeds and precision of rotation;
- they generate less heat;
- they show higher rigidity.

Durability of precision rolling-element bearings is considerably affected by the method of lubrication and selection of a suitable lubricant.

Lubrication of rolling-element bearings is aimed at:

- reduction of rolling friction between bearing races and rolling elements;
- reduction of wear of mating parts in the bearing: rolling elements, races, cages;
- transfer of excess heat from the bearing;
- protection against corrosion;

- removal of solid foreign bodies: wear products from friction surfaces, atmospheric dust, oil deposits.

Bearings can be lubricated with oil mist (high-speed bearings), oil or solid lubricant. The method of using solid lubricants is highly recommended today. In cased and sealed bearings, one-off dose of lubricants is enough for the whole period of bearing life.

The emerging method of lubricating high-speed bearings is dosing small amounts of oil at the pressure of 0.4 MPa. Oil injection between rolling elements and races is performed periodically from several nozzles located throughout the bearing circumference. Supplying an optimal amount of oil directly on the bearing surfaces provides better working conditions compared to oil mist lubrication.

3. COMSOL Multiphysics

COMSOL Multiphysics is a simulation package which uses finite elements method (FEM) for computational analysis in one, two or three dimensions. Its flexibility and practical characteristics allow for concentration on the modelled phenomena without the necessity of being much experienced in using the software. One advantage of *COMSOL Multiphysics* lies in an intuitive and efficient graphical user interface (GUI) which allows for fast and convenient creation of models, simulations and visualization of the results. Through experimenting with different variables and geometry of the modelled object, users can quickly familiarize with and understand the effect of different parameters on the performance of the whole system. This facilitates future advanced analysis of the system, design and optimization.

COMSOL Multiphysics allows for easy investigations, simulations and analysis of complex phenomena which occur in the modelled system. It is used for different domains of engineering and scientific applications.

COMSOL is the first simulation package which uses multi-domain modelling. Many different physical phenomena can be described and modelled in the investigated systems, obtaining the results which reflect the behaviour of an actual system in a very accurate manner (***, 2010).

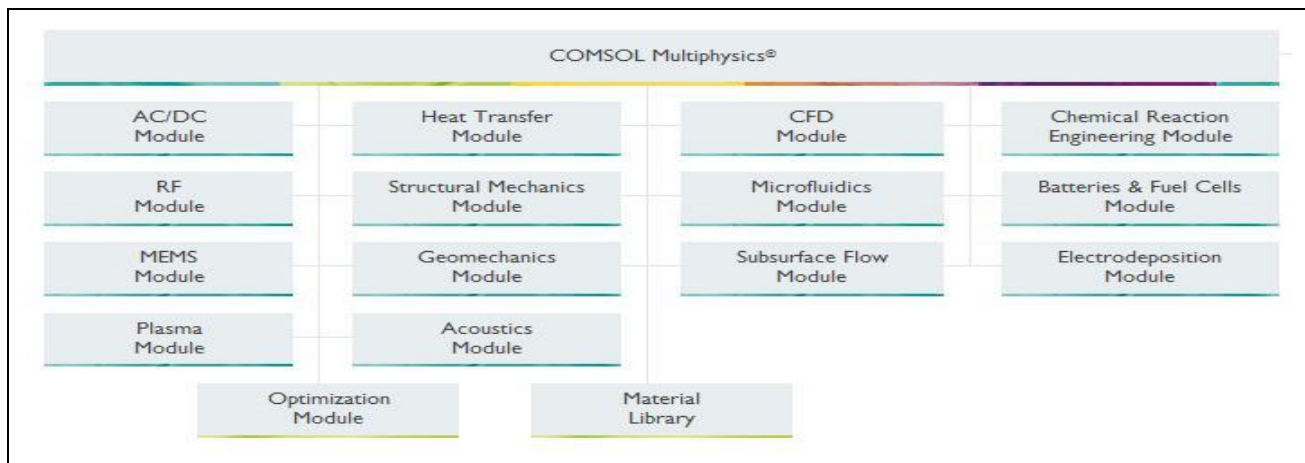


Fig. 2. Available modules of *Comsol* software

3.1 Extension Modules

Comsol system features special-purpose modules which provide convenient working environments for specific domains of science. They are based on standard terminology, material libraries, specialized solutions and elements, and suitable visualization tools. All of them operate with individual instructions and model libraries, which provide complete solutions for a particular domain. The software contains a series of available modules presented in Fig. 2 (***, 2011).

3.2 Structural Mechanics Module

Computational analysis of machine tool spindle systems was carried out using *Structural Mechanics Module*. The module solves the problems in the domain of solid body mechanics, using special elements, such as beams, plates and shells. It allows for static and dynamic testing with different frequencies and provides opportunities for fatigue analysis and linear buckling. It allows for the definition of load, material limitations and models in global coordinate system or only in the coordinate system defined by the user. All types of applications in this module are entirely compatible, which allows for combining the tasks with other modules.

Structural Mechanics Module features additional sub-modules which allow for static, eigenfrequency, damped eigenfrequency, frequency response, parametric, quasi static, time-dependent and linear buckling analysis.

4. Modelling of Spindles in COMSOL System

After opening the program in the *Model Navigator* screen, a graphical configuration 3D and *Structural Mechanics Module* were selected (Grzesiak, 2010).

After setting the grid size, the creation of the model of a spindle was started through selecting the *Cylinder* option from the side toolbar. Next activities of adding drawing primitives led to the development of the initial model of a spindle (Fig. 3).

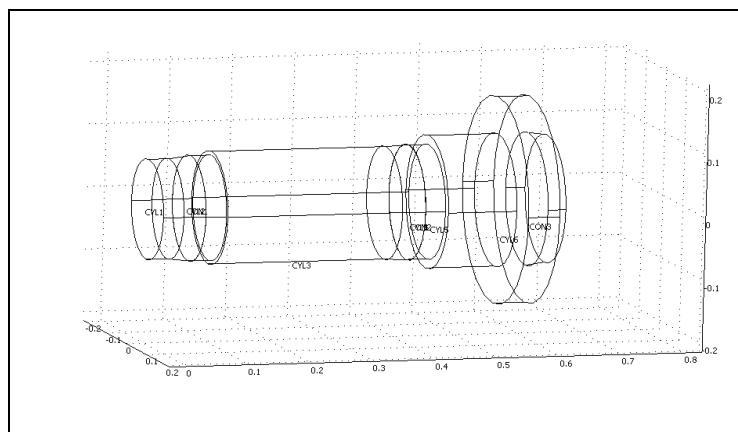


Fig. 3. Initial model of a spindle

All the parts of the modelled spindle were grouped into a single component by selecting the *Union* option available from the side toolbar.

In order to add the hole passing through the entire spindle length, a cylinder with suitable dimensions and the *Difference* option were used.

An important stage in modelling is selection of the method of load in the spindle caused by cutting forces. This can be achieved using the *Physics* tab and selecting the *Point Settings* option. Value of the cutting force was input in *Loads* screen in consideration of the direction and sense (Fig. 4). The *Point Settings* screen also allows for inputting support reactions in the *Constraint* tab.

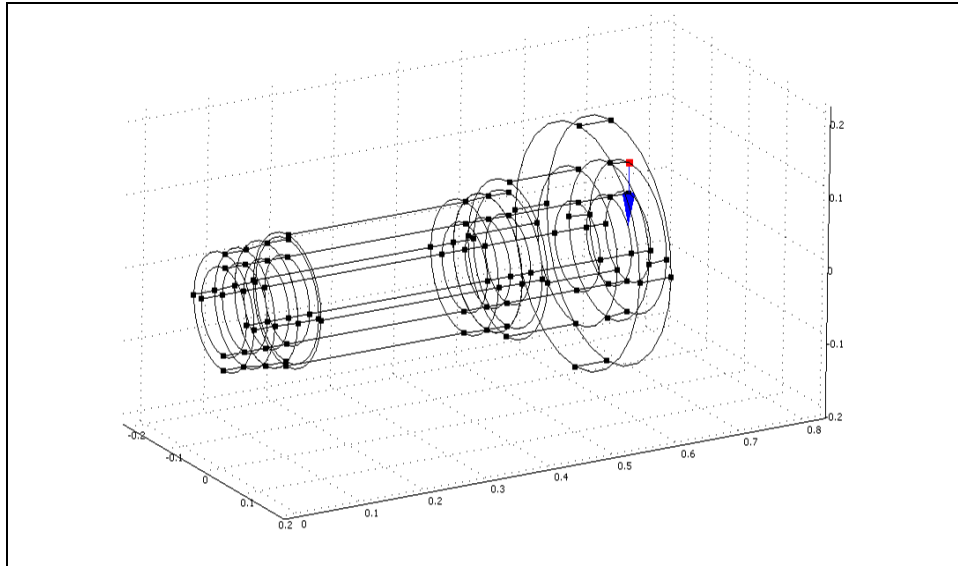


Fig. 4. Modelling load from cutting forces

The next stage involved modelling of the location of bearings in the spindle. The option *Boundary Settings* was selected in the *Physics* tab. The bearings were modelled as the surfaces with evenly distributed load corresponding to bearing capacity (Fig. 5). In order to input the values of displacements, the *Prescribed Displacement* option in the *Constraint Condition* tab was selected.

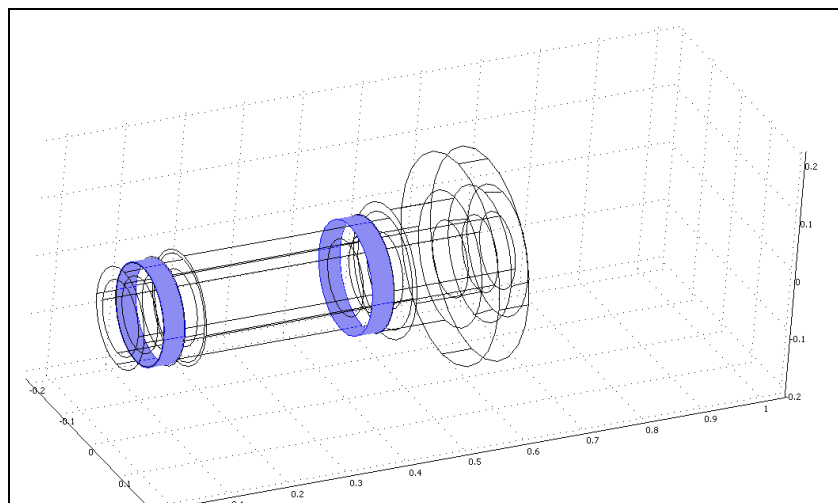


Fig. 5. Modelling of bearing supports

Another stage in building the model was adding front end of spindle chuck with the jaws. The dimensions of the chuck were copied from the catalogue of *Bison-Bial S.A.*, which is a manufacturer of apparatus and chucks for machine tools (***, 2009). The chuck was modelled as a flange with jaws mounted on it (Fig. 6).

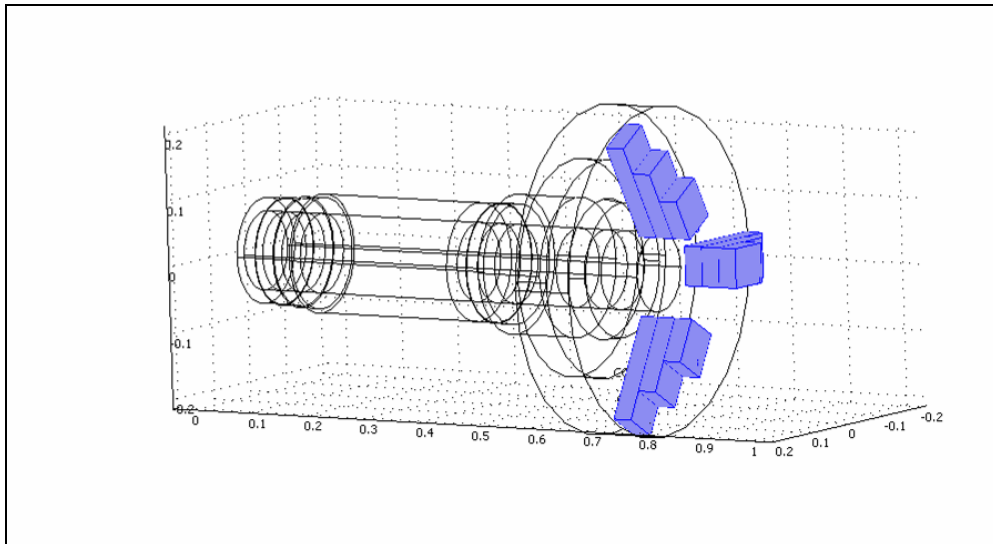


Fig. 6. Model of a spindle and spindle chuck

In order to define the materials for individual parts of the model, *Physics* was selected from top menu and then *Subdomain Settings*. The *Material* screen was selected from the available library for choosing the type of material for the components of the model. When selecting the material, the system loads automatically such parameters as Young's modulus, Poisson's ratio and others.

The finished model of the spindle with spindle chuck was covered with the mesh of finite elements. The *Mesh* tab and the *Free Mesh Parameters* screen were selected from the menu. The *Remesh* option generates the mesh automatically (Fig.7).

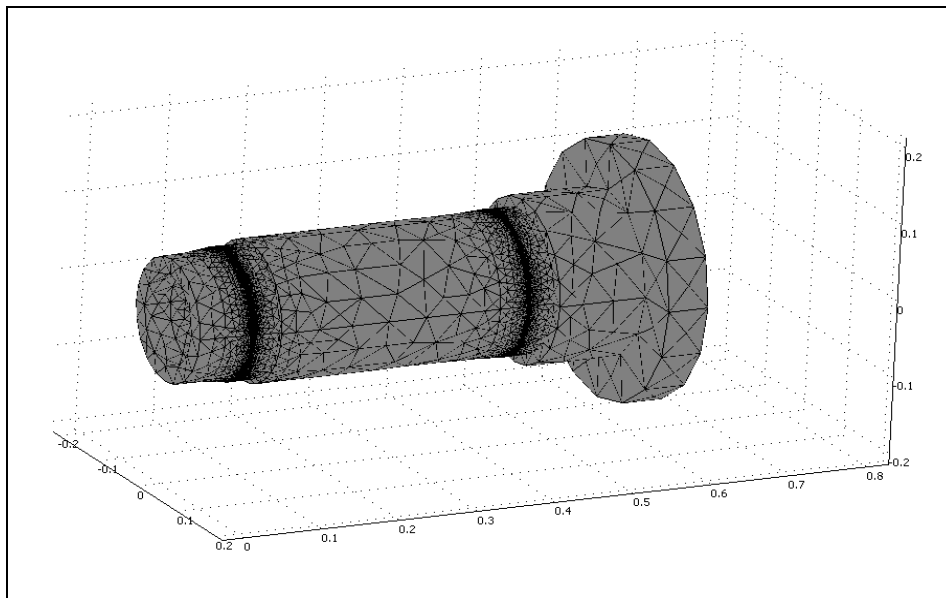


Fig. 7. The spindle model covered with the mesh

The final stage of using *COMSOL* system with *Structural Mechanics Module* was to carry out computations. The main menu was used to select the *Solve* tab and the *Solver Parameters* screen, where the type of computation was selected. The *Static* option was selected for static computations, whereas dynamic computations were carried out using *Eigenfrequency* option.

In order to present the obtained results, the *Postprocessing* tab and *Plot Parameters* screen were selected. They allowed for resizing the visible model deformation or using a function of generating and playing animations.

5. Analysis of Machine Tool Spindle Assembly in COMSOL System

Using the possibilities provided by *COMSOL* system, a computation analysis of the model of machine tool spindle assembly (presented in Fig. 8) was carried out. The model was developed based on the actual design of a medium-size lathe. Three angular ball bearings B7018, divided with spacers, with a particular value of pretention, were used in the front support. The rear support was provided by a single cylindrical-roller bearing NN3016K with internal tapered hole with 1:12 taper. Linear displacement of the internal ring of the bearing changed value of clamping rolling elements between bearing rings (Grzesiak, 2010).

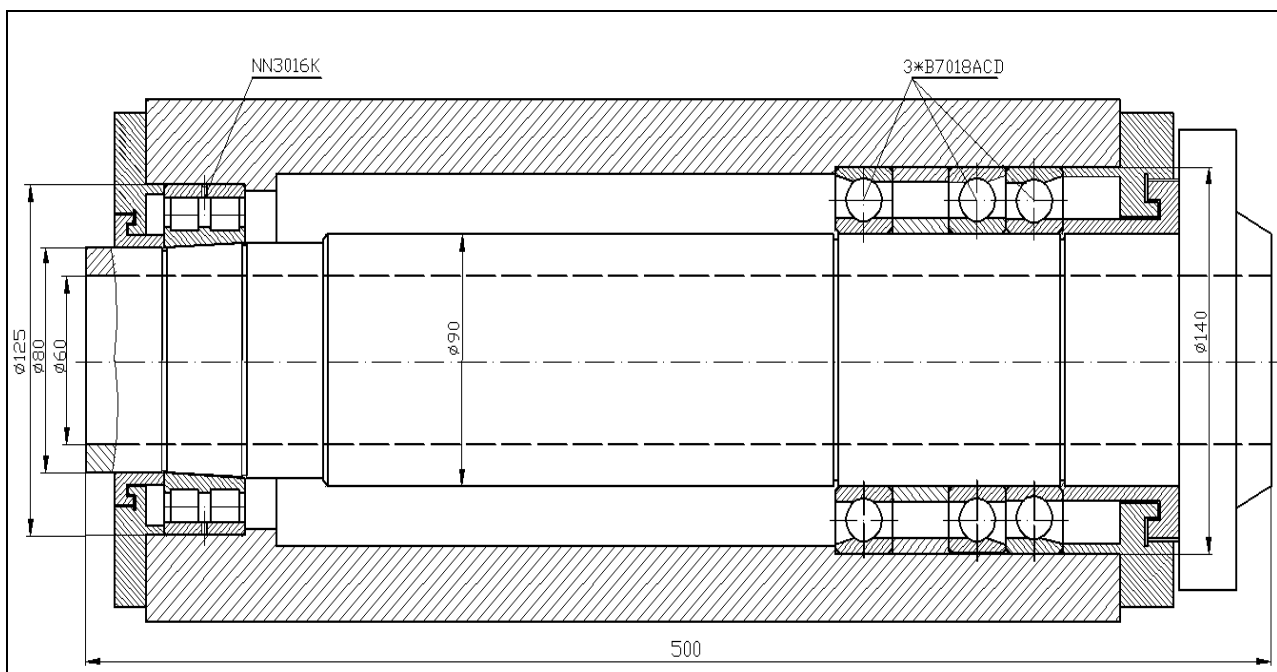


Fig. 8. Model of machine tool spindle assembly

In the static range, the computations were carried out for two values of the resultant cutting force: $F=4000$ N and $F=6000$ N.

The computational analysis in the dynamic range consisted in determination of the first three frequencies of free vibrations and the corresponding mode of vibration. The computations concerned the model of the spindle and the model of the spindle with spindle chuck and the representative workpiece.

Fig. 9 presents the deformation of the geometry of the analysed model of spindle assembly in the machine tool. The change in colour marks the locations which are the most susceptible to static deformations generated by the load. Spindle displacement at the cutting point for the force $F = 4000$ N was $93 \mu\text{m}$.

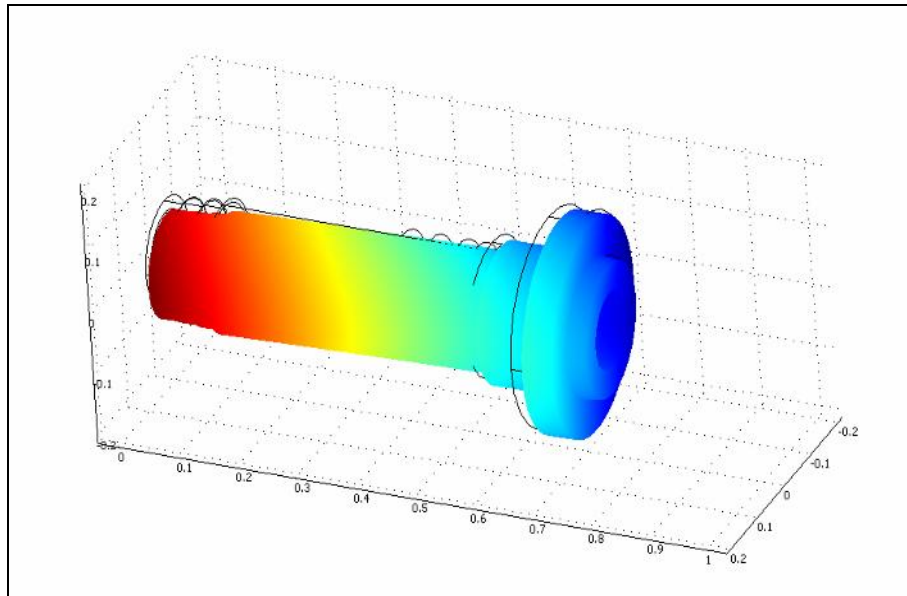


Fig. 9. Static displacement of spindle model for the load force of $F = 4000\text{N}$

The result of the dynamic analysis was the determination of three first frequencies and the corresponding modes of vibrations. For the model of spindle, the first frequency of free vibrations amounted to 1065 Hz, second frequency being 1294 Hz and the third 1802 Hz. The mode of free vibration corresponding to the second frequency is presented in Fig. 10.

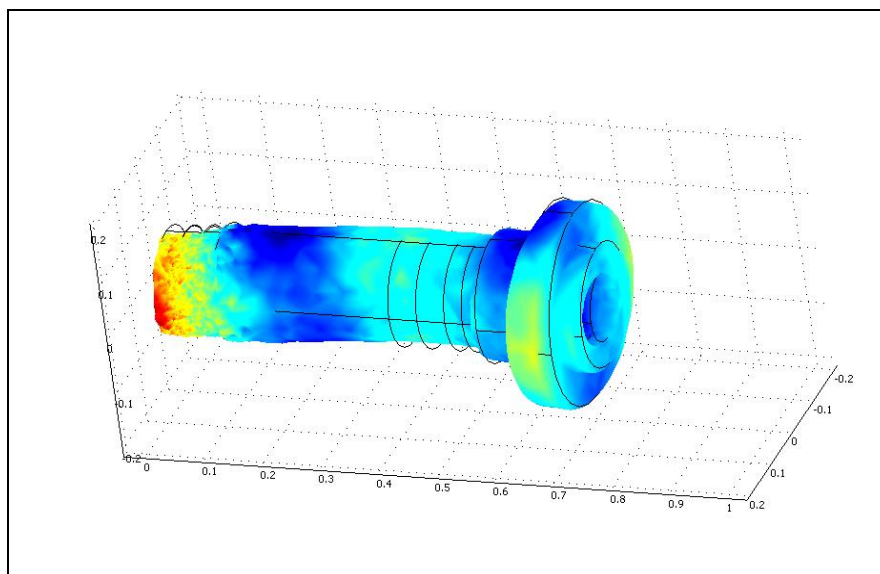


Fig. 10. The mode of free vibrations corresponding to the second frequency
 $f_2 = 1294\text{Hz}$

After the dynamic analysis of the model of spindle with self-centring three-jaw chuck with the diameter of $\phi 250\text{mm}$ and length of 95mm, and the representative workpiece with 91.5 mm and length of 88 mm, the following values of three first frequencies of free vibrations. The first frequency of vibration was 287 Hz, with 563 Hz for the second frequency and 722 Hz for the third one. Figure 11 presents the mode of free vibrations in spindle model for the third frequency $f_3 = 722\text{ Hz}$.

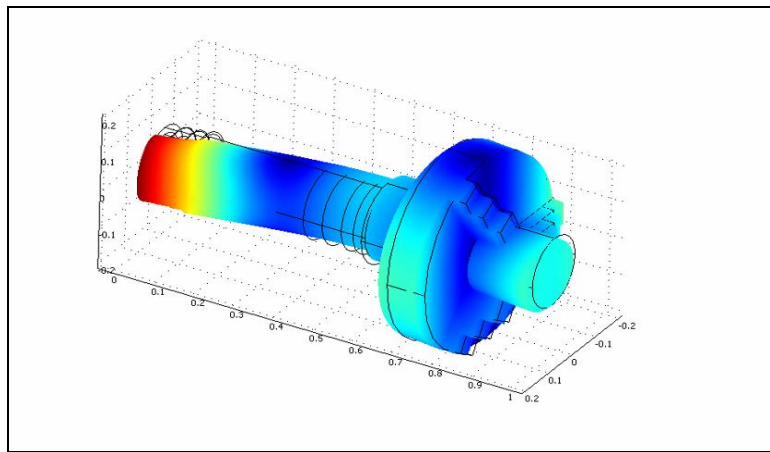


Fig. 11. The mode of free vibrations for the third frequency $f_3 = 722\text{Hz}$.

6. Conclusion

The study confirmed the usefulness of *COMSOL Multiphysics* computer software for computational analysis in machine tool spindles.

The study demonstrated the opportunities for effective creation of geometrical models of spindles, modelling of load from cutting forces and bearing support and connection of the spindle with the model of spindle chuck and the workpiece. The available library of materials was used for selecting materials for individual components of the model of spindle assembly.

An advanced computational module allowed for fast processing of complex computations. The obtained results could be analysed in the form of graphical representation of model deformation and playing an animation.

The *COMSOL* system was used for the computational analysis of the spindle model in medium-size lathe. The values of displacements and deformation of the spindle for the two values of load were determined within static range. Dynamic analysis allowed for the determination of the first three frequencies of free vibrations and the corresponding modes of vibrations of the spindle model.

The *COMSOL* system can be successfully used for modelling and computational analysis of the machine tool spindles and other machine parts and technological equipment.

7. References

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