Spindle analysis using numerical methods

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Abstract: Spindles are fundamental to most machine tools. The complexity of static behavior study for spindle-assembly, given the variety of design and its different dimensions, it constitutes a focus of research in structural and functional parameters that determine the variable dependencies between many complex and sometimes difficult to assess. In the above context, this paper aims to highlight the importance of studying through introduction of additional ball bearing in the front of the spindle, and how it influences the stress and arrow for the spindle studied. Because the solutions are difficult to obtain, the system being undetermined, we have to use the numerical methods.

Key-Words: Spindle, Bearings, Machine tools, Milling machine, Stiffness, Finite element method, COSMOS/M

1 Introduction

The trends toward increased throughput of machining processes and toward tighter tolerances will cause spindle analysis to become more important. Modern machine tools have stiff structures and accurate positioning capabilities. The weak link in a modern machine tool is often the spindle [1].

Choice of bearing supports and bearing seating, as well as assembly related problems, such as insufficient pre-loading of bearings and their inadequate interference fitting to the shaft cause out of balance rotations of spindle, which in many cases contribute significantly to the vibrations of the spindle [2].

Spindle assembly is in an elastic system of shaft - bearing, which in most cases consists of one or more bearings. The static behavior that in its assessment should consider the following aspects: aspects regarding bearing construction, the scheme of loading and the operating conditions.

Aspects regarding bearing construction are: coaxially effect of deviations from the bearings and shaft; bearings used and the influence of their position to the camps; influenced arrangement of bearings; thrust bearings preload-effect; determination more precise static radial and axial stiffness of the bearings.

Aspects regarding the loading scheme are: vector-cutting forces can be applied (in the end-spindle or in the end console to the main shaft); drive-shaft torque can be applied between the shaft bearings at a fixed distance from the first or from the back bearing [5]. Aspects related to operating conditions for spindle: vertical position or horizontal position.

The subject has been studied in terms of the three main aspects: influence the number of bearings used and their position on the spindle, for horizontal spindle position, forces being in the console application and the driving outside the camp.

The spindle is made of steel 41MoCr11 SREN 10083-3:2017, housing system consisting of radial thrust ball bearings sets 7010 ATA.P4.DT, ϕ50x ϕ80x 32 and ϕ50x ϕ80x16 for front side and set of radial thrust ball bearing 7008 ATA.P4.DB, ϕ40x ϕ68x30 for back side.

2 A brief overview of numerical methods

The need for numerical methods arises from the fact that for most practical engineering problems analytical solutions do not exist. While the governing equations and boundary conditions can usually be written for these problems, difficulties introduced by either irregular geometry or other discontinuities render the problems intractable analytically. To obtain a solution, the engineer must make simplifying assumptions, reducing the problem to one that can be solved, or a numerical procedure must be used [3]. In an analytic solution, the unknown quantity is given by a mathematical function valid at an infinite number of locations in the region under study, while numerical methods provide approximate values of the unknown quantity

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only at discrete points in the region [7]. In the finite element method, the region of interest is divided up into numerous connected sub regions or elements within which approximate functions (usually polynomials) are used to represent the unknown quantity.

The finite element method is one of the most powerful approaches for approximate solutions to a wide range of problems in mathematical physics. The method has achieved acceptance in nearly every branch of engineering and is the preferred approach in structural mechanics and heat transfer [4].

The physical concept on which the finite element method is based has its origins in the theory of structures. Knowing the characteristics of individual structural elements and combining them could obtain the governing equations for the entire structure. This process produces a set of simultaneous algebraic equations. The limitation on the number of equations that could be solved posed a severe restriction on the analysis. The introduction of the digital computer has made possible the solution of the large-order systems of equations.

The finite element method (FEM) is a powerful technique originally developed for numerical solution of complex problems in structural mechanics, and it remains the method of choice for complex systems. In the FEM, the structural system is modeled by a set of appropriate finite elements interconnected at points called nodes.

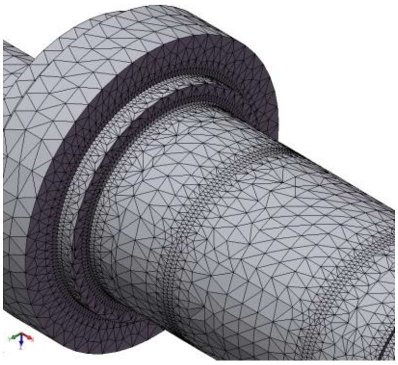

Fig.1 Tetrahedral elements meshing.

General equations of the finite element method, for static problems, are expressed by matrix equations:

$$[K]\cdot\{\delta\}=\{F\}+\{F\}_{\varepsilon_0}+\{F\}_p \qquad (1)$$

where: $\{F\}$ is the vector of external nodal forces; $\{F\}_{\varepsilon_0}$ - the vector of nodal forces due to incipient internal stresses; $\{F\}_p$ - vector forces caused by distributed loads; $\{\delta\}$ - nodal displacement vector.

The formulas defining the elements of these matrices and vectors are:

$$[K]^e=\int_E [B]^T[D][B]dV \qquad (2)$$

$$[F]^e_{\varepsilon_0}=\int_E [B]^T[D]\{\varepsilon_0\}dV \qquad (3)$$

$$[F]^e_p=\int_E \left[N^T\right]\{p\}dV \qquad (4)$$

where: $[N]$ is the form element matrix; $[D]$ - material elasticity matrix; $[B]$ - linking matrix between specific deformations and nodal displacements; $\{\varepsilon_0\}$ - initial specific strains vector; $\{p\}$ - distributed loads vector.

Finite element analysis through COSMOS/M is applied in this paper. COSMOS/M is a complete, modular, self-contained finite element system developed by Structural Research and Analysis Corporation (SRAC) for personal computers and workstations. The program includes modules to solve linear and nonlinear static and dynamic structural problems, in addition to problems of heat transfer, fluid mechanics, electromagnetic and optimization. Modules for such special analysis options as fatigue are also available. The system is constantly developed and maintained by using state-of-the-art techniques and up-to-date hardware capabilities.

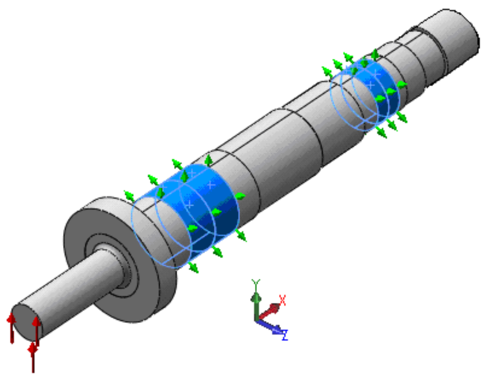

Fig.2. Surfaces that require zero radial displacement and the application of forces mode.

COSMOS/M offers a comprehensive set of finite elements to analyze structural, thermal, fluid flow, and electromagnetic problems. The elements are grouped in the COSMOS/M element library under different classifications for linear structural analysis, nonlinear structural analysis, thermal analysis, fluid flow analysis and electromagnetic analysis. Every element type is identified by a name. In many cases, the same elements can be used in different analysis types. In this case, solid element (SOLID) is used.

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For SOLID element library is necessary to know geometrical model, special features, element group options, real constants, material properties and element loading. The results can be consulted under graphical form (color map and diagrams) respective numerical values.

3 Static behavior of spindle-assembly using finite element analysis

In many practical problems, the specific strain-displacement linearity, stress-specific strain respectively, define by specific set of equations of elasticity theory are not preserved, that a fair settlement can be done only by a numerical analysis [6]. In order to predict static behavior a three-dimensional finite element model has been developed by the COSMOS/M code.

To determine the displacements and strains, the structure was discredited with solid type volume elements (SOLID library element program COSMOS/M). Tetrahedral elements were used for spindle meshing and in the connection areas of the jump-start and end diameter of the shaft support using a finer mesh. Average amount of edge elements was 5 mm and the fine mesh has reached a size of 0.5 mm. Tetrahedral element meshing was represented in figure 1.

Determination of stresses and displacements were performed considering the following boundary conditions: bearing area required radial displacement equal to zero over a distance determined by the first and last ball bearing centers of that housing; on the coupling flange is considered that nodes located on cylindrical surfaces of the holes are blocked.

The study took into account the tool mounted in the spindle; the maximum force is taken into account for the iron machining of 2500 N.

Figure 2 represented areas for which radial displacement is considered void, place and mode of action of cutting forces.

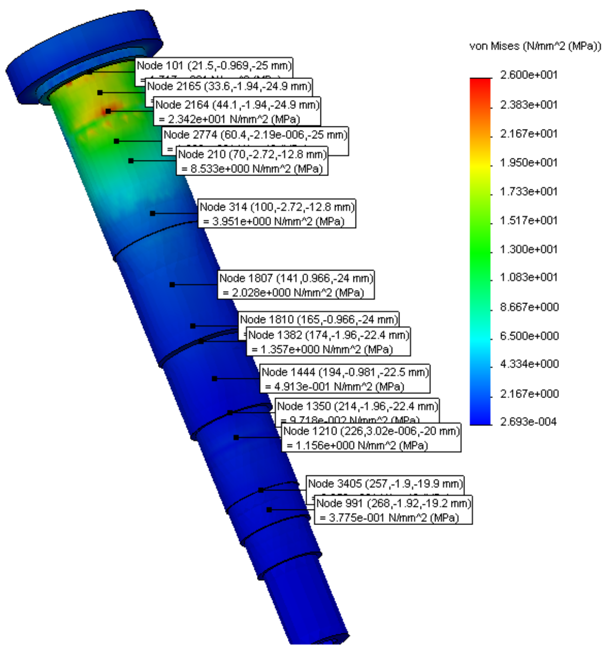

Fig. 3. Nodes selected for the study of stress.

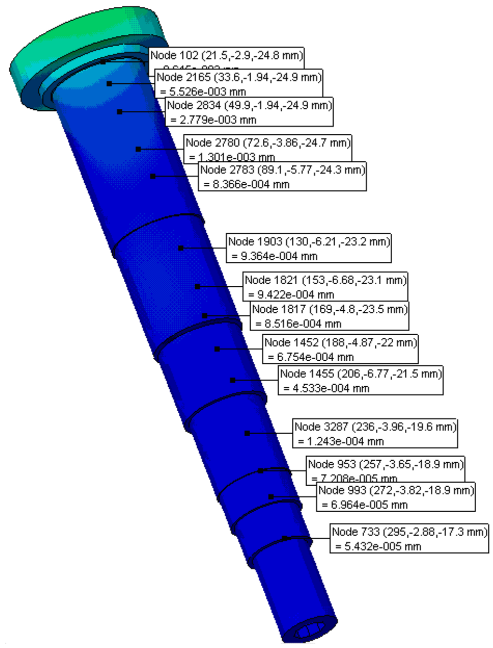

Fig. 4. Nodes selected for study of displacements.

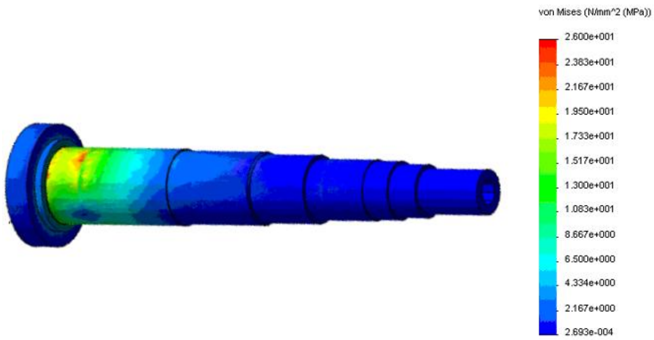

Fig. 6. Equivalent stress field on the spindle surface.

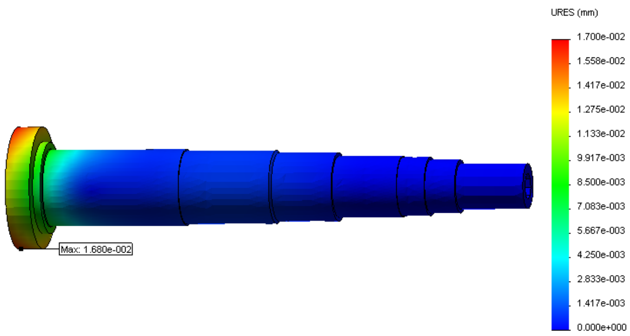

Fig. 8. Equivalent displacement field on the spindle surface.

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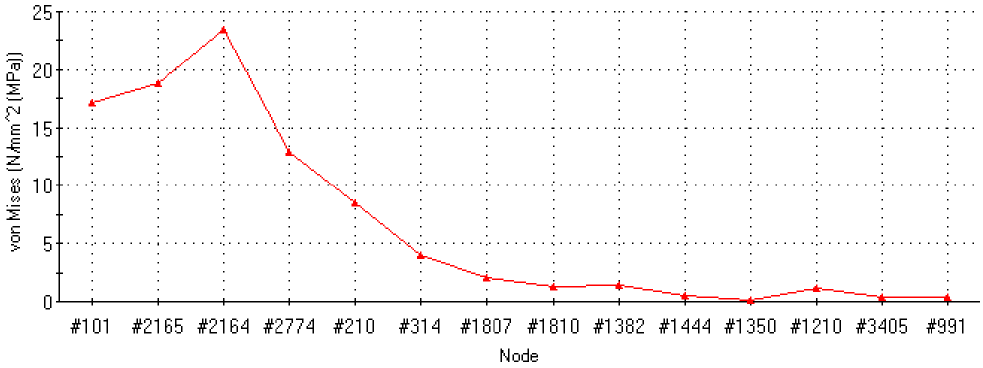

Fig.7. Variation of equivalent stress in the specified nodes.

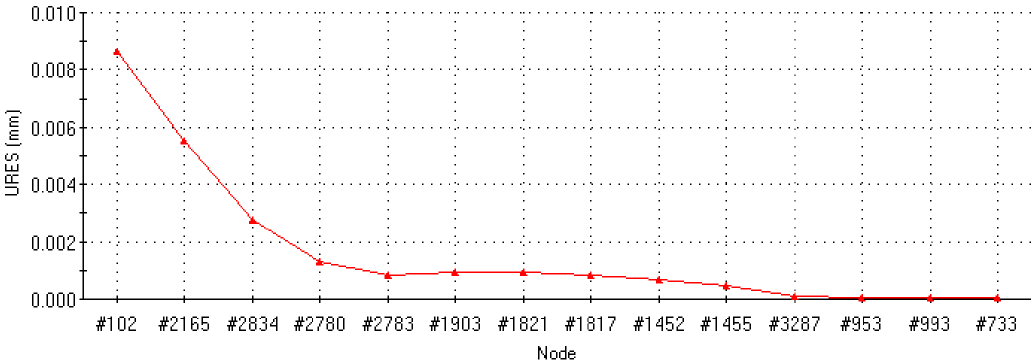

Fig. 9. Variation of displacements in the nodes specified.

Nodes selected for study those stress and displacements are presented in figure 3, respectively figure 4.

A first analysis was done to the horizontal spindle, supported horizontally on two bearings, to taking into consideration two sets of bearing in front (case a) and in the latter case taking into account three sets of bearings (case b), the variants are presented in figure 5.

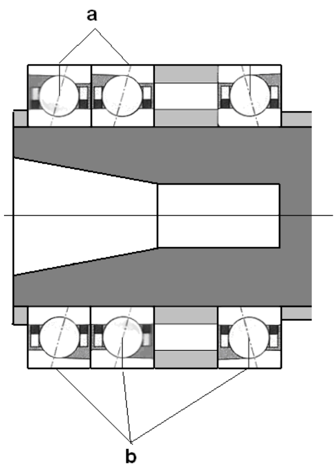

Fig. 5. Support cases studied:
a) two bearings; b) three bearings.

In the first case, equivalent von Misses stress field on the spindle surface studied was represented in figure 6.

The stress field analysis shows that maximum values are on the outer surface of the spindle, proximity space of bearing in front (figure 7).

The study continues with field of displacements in the same spindle configuration, results are represented in figure 8 and in figure 9 the variation of displacements.

Displacements analyses show that they have the maximum values on the surface of the flange, having a downward trend.

4 Optimization of horizontal spindle bearings

Taking into account the third bearing from front housing and inner rings of bearings, the equivalent stress field was represented in figure 10 and their variation in figure11.

Figure 12 shows the equivalent displacement field on the spindle surface, in case of three bearings with inner ring mounted.

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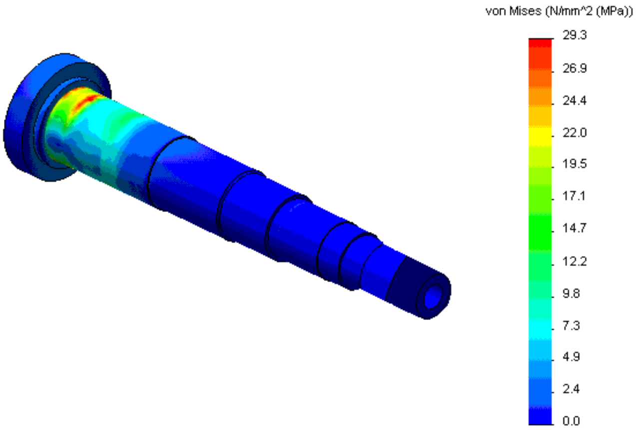

Fig.10. Equivalent stress field on the spindle surface, in case of bearings with inner ring mounted.

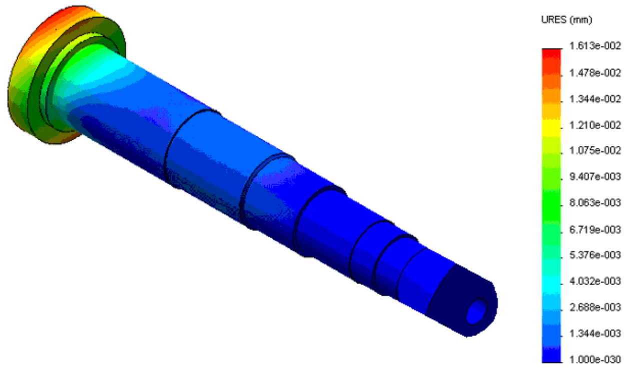

Fig. 12. Equivalent displacement field on the spindle surface, in case of bearings with inner ring mounted.

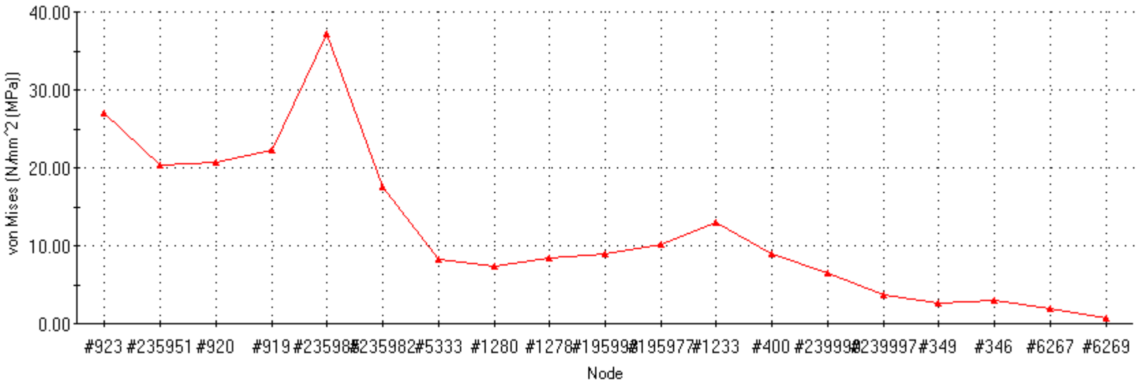

Fig. 11. Variation of equivalent stress in case of spindle bearings with inner ring mounted.

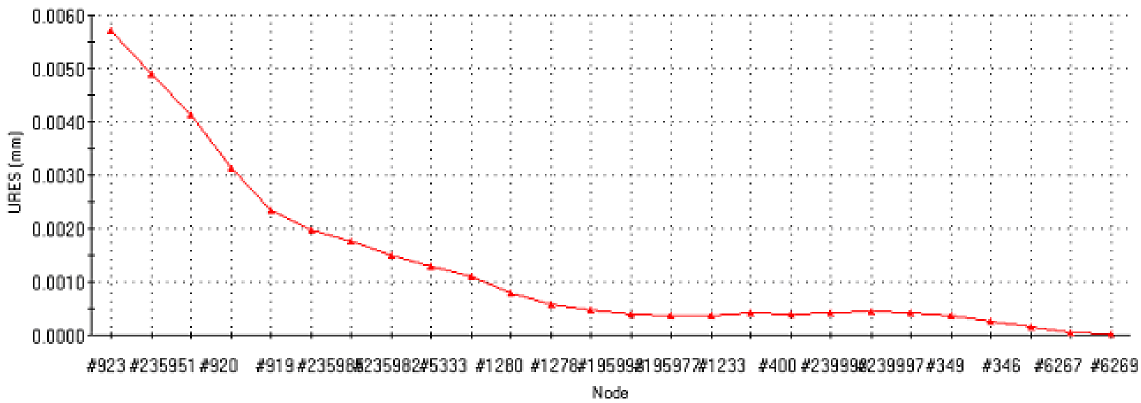

Fig. 13. Variation of displacements in case of spindle bearings with inner ring mounted.

It is found that installation of the additional bearing in front of the spindle, leads to increased tensions in the area of the third bearing with significant values to the previous case, simultaneously with the occurrence of additional tensions in the back bearing.

Comparing the diagrams presented in figures 9 and 13, it finds that in case of assembly without additional bearings, arrow at the end of the spindle is 0.0084 mm, and if additional bearings are mounted, the arrow is 0.0057 mm, resulting in a difference of 0.0027 mm. If this decline seems small in value, it represents 32% of the initial arrow.

This explains the importance of supplementary bearing fitted in the front spindle housing.

5 Conclusions

The following aspects are marking out from this study:

- uniform distribution of stress on the front and back bearings;
- arrow decreasing to the cutting tool mounting flange enable increases of processing accuracy;
- the possibility of studying the behavior of spindle assembly by numerical methods for the three bearings mounted to small intervals, difficult to marking out by analytical methods;
- increase spindle stiffness by decreasing the arrow, which influences positive the dynamic behavior of spindle assembly at high speeds;
- choosing an optimal distance between the front housing bearings in case of mounting the third ball bearing;
- possibility of taking into account the influence of bearing rings of front spindle housing on arrows and tensions.

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