Structural Optimization of Journal Porous Metal Bearing

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Selflubricating sliding bearings production and investigations are still in great expansion because of their very practical maintenance and very long operating life. This is probably a very important reason for their common use in most of modern machines and mechanisms, where porous metal bearings take a leader position. With some new simulation methods and software tools it is possible to make qualitative analysis of sliding bearing behavior taking elastic deformations in account. This paper presents structural optimization of journal porous metal bearing under complex load distribution. Surface of porous metal bearing is loaded inside with pressure distribution that is calculated by hydrodynamic lubrication theory. Besides, there is also frictional force loading inner surface and nonuniform temperature distribution on bearing volume. The structure analysis is made for each kind of load separately and for complex load distribution of bearing. This analysis is realized by finite elements method (FEM) in structure analysis module of CATIA V5R11 software. Based on analysis results, in the second part of the paper is given parameter optimization of porous metal bearing with taking elastic deformations of bearing shell into account. These simulations, analysis and optimizations realized in CATIA are covered and illustrated with corresponding pictures and diagrams.

Keywords: *Porous metal bearing, structure analysis, finite element method, elastic deformations, structural optimization*

1. INTRODUCTION

Sliding bearings are so much in use today, which means they are applied to most of machines that we need and meet in whole our life. This can be understandable because of some advantages that this sort of bearing has compared with rolling bearings. Generally, their production is not so complicated, which makes the price lower, for simple mounting they can be made in parts, and in operating they produce less noise and vibrations. In case of correct lubrication, all sorts of sliding bearings are very practical for maintenance and they have long operating life, which are probably most important reasons for their common use. Especially, selflubricating sliding bearings are very useful in the new age and there are two different sorts of them:

Sliding bearings that work without using any amount of oil or grease. These bearings are made of plastics, graphite or ceramics materials.

Sliding bearings that contain lubricant, either in special storage or in their own material structure. The best example and best-known in this group are porous metal bearings made by sintering process and they are the product of powder metallurgy [1].

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In the world today, it's essential to design a new "best system", or to optimise some existing one, which means efficient, unique and cost effective system.
Increases with the Human expenses lead to an increase of machine automation and thus to new trends and methods application. At the same time, with this increase due to the energy cost increase a need to make a friction coefficient as low as possible. The goal of the emission minimization requires the employment of as little a lubricant as possible and/or the avoidance of emissions from porous metal bearing as a tribosystem. The tendency to minimize the price leads to as comprehensive standardization with few construction units as possible and, on the other hand, to the necessity of optimization of the systems. It is common to all trends that the load universe for Tribosystems can be constantly intensified and often mastered only by the employment of new technologies and the following trends [2]:

- Development of materials of some hydrodynamic and/or elastohydrodynamic lubrication with lowest friction coefficient at high temperatures if possible.
- Development and use of formulas, models and tools for methodical specifying and optimization of the tribological construction, as a support for the design and designer.
- Rising the necessity to unite tribological and ecological requirements e.g. the lubrication with lubricants will increase development of guidance on water basis.

- Development of guidance, where only more arises a smallest temporary discrete contact between the friction bodies (magnetic, aerodynamic or hydrodynamic bearing).

Concerning these trends, optimum design concepts and methods [3] help us to design such “best” system of journal porous metal bearing, as one of typical engineering applications. Developments of well known software tools for analysis and optimization which last for years are additional help to reach this objective. Using software CATIA for stress analysis by Finite elements method (FEM), it is also possible to make parameter optimization by taking elastic deformations of bearing shell in account. Besides hydrodynamic lubrication theory that is common in use for calculation of journal bearings, this way of analysis presents a very qualitative step towards elasto-hydrodynamic lubrication model of porous metal bearing. In this paper only bearing shell is analysed, because it is most important and interesting for structural optimization. This can be done, even real porous metal bearing works in assembly with shaft (white) and housing (black), like a group of bearing testing machine, as shown in Fig. 1.

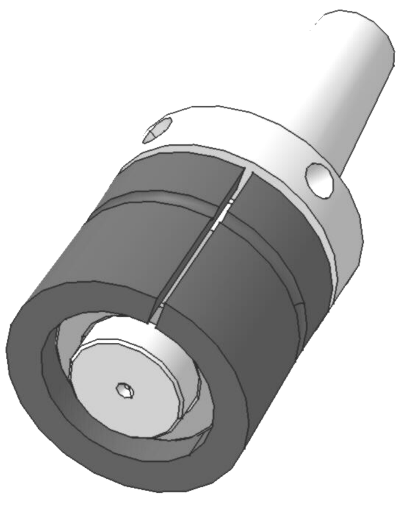

Figure 1. Assembly of bearing, shaft and housing

2. BEARNIG STRESS AND DEFORMATION

The main supposition for all stresses (σ, τ) and deformations (ϵ, γ) analysis is their linear dependence:

$$\sigma = E\epsilon \text{ and } \tau = G\gamma . \quad (1)$$

Deformations in transversal direction of radial force are taken into account using Poisson coefficient (ν_p) and deformations by temperature variation is $\epsilon_t = \alpha_t \, \Delta T$. If we are analyzing stresses and deformations on bearing volume with known main directions, it is possible to write equations of stresses in these directions [4]:

$$\sigma_1 = \frac{E}{1-\nu_p{}^2}\left[\left(1-\nu_p\right)\epsilon_1 + \nu_p\left(\epsilon_2+\epsilon_3\right)\right], \quad (2)$$

$$\sigma_2 = \frac{E}{1-\nu_p^2}\left[\left(1-\nu_p\right)\epsilon_2 + \nu_p\left(\epsilon_3+\epsilon_1\right)\right], \quad (3)$$

$$\tau_{12} = \tau_{23} = \tau_{31} = 0 ,$$

$$\sigma_3 = \frac{E}{1-\nu_p^2}\left[\left(1-\nu_p\right)\epsilon_3 + \nu_p\left(\epsilon_1+\epsilon_2\right)\right]. \quad (4)$$

and equations for deformations in these main directions:

$$\epsilon_1 = \frac{1}{E}\left[\sigma_1 - \nu_p(\sigma_2+\sigma_3)\right], \quad (5)$$

$$\epsilon_2 = \frac{1}{E}\left[\sigma_2 - \nu_p(\sigma_3+\sigma_1)\right],$$

$$\gamma_{12} = \gamma_{23} = \gamma_{31} = 0 , \quad (6)$$

$$\epsilon_3 = \frac{1}{E}\left[\sigma_3 - \nu_p(\sigma_1+\sigma_2)\right]. \quad (7)$$

These relations could not be directly used for stress and deformation calculation values of porous metal bearing because of complex bearing load. For such problems it is very useful to apply Finite element method (FEM) that could be realized using numerous software tools.

In general, the (FEM) analysis consists of three main phases:

Preprocessing or problem definition phase,

Process or calculation phase,

Post processing or results analysis phase.

2.1. Preprocessing phase

In this phase of problem definition, the first task is to form such net of proper finite elements dimensions and form in order to cover object mass, volume or surface with satisfying accuracy. The choice of finite elements form and dimensions certainly depends of analyzed object shape and it should follow the expected stress distribution.

Here porous metal bearing with dimensions $\varnothing 30/\varnothing 20\times 20$ mm is analyzed, where linear elastic tetrahedron is chosen for finite element, as four nodes isoparametric solid element [5]. This element has three degrees of freedom (translations) per node (N1,....,N4), with gravity center P1, as showen by Fig.2.

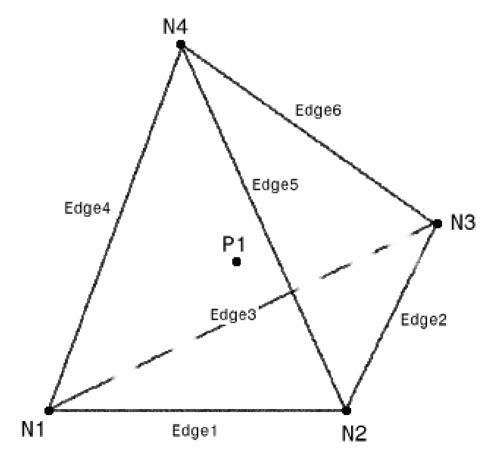

Figure 2. Linear tetrahedron finite element

The porous metal bearing volume consists of 9153 tetrahedrons with dimensions of 1.88mm, which means there are 2208 nodes, as shown in Fig.3.

For modeling porous metal bearing, it is to be taken in account physical and properties of bearing material that are of importance for analysis process. In this case bearing is made of bronze alloy with mechanical and other properties given in Table 1.

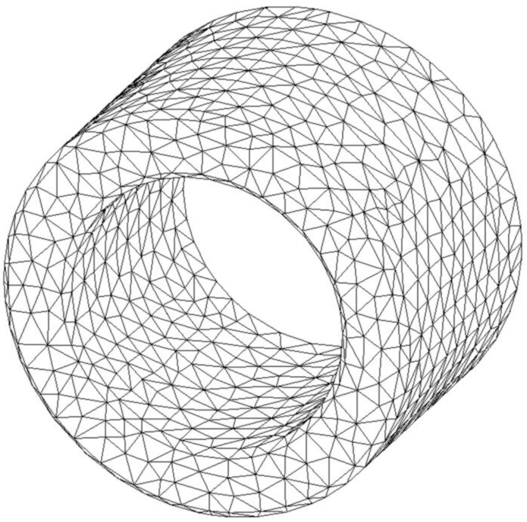

Figure 3. Porous bearing as finite elements net

After that, of great importance in preprocessing phase is correct definition of complex bearing load. Radial load on bearing is defined by nonuniform pressure distribution of lubricant on the inner surface of bearing. Starting from a well known Reynolds equation for porous metal bearing (8), following hydrodynamic lubricating theory [6], nonuniform pressure distribution of thin oil layer is calculated (9):

$$\frac{\partial}{\partial x}\left(\frac{h^3}{\eta}\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial z}\left(\frac{h^3}{\eta}\frac{\partial p}{\partial z}\right)=6U\frac{\partial h}{\partial x}+12\frac{\Phi}{\eta}\left(\frac{\partial p^*}{\partial y}\right)_H , \quad (8)$$

$$p=\frac{3\upsilon\eta}{rc^3}\left[\frac{\varepsilon\sin\theta}{\left(1+\varepsilon\cos\theta\right)^3+12\Psi}\right]\left(\frac{b^2}{4}-z^2\right). \quad (9)$$

Table 1. Bearing material properties

Properties of material CuSn10	value	dimens.
E - Young modulus	$1{,}12\cdot10^5$	N/mm^2
ν_p - Poisson ratio	0,341	-
ρ_l - Density	6500	kg/m^3
α_t - Therm. expans. coeff.	$17{,}8\cdot10^{-6}$	K^{-1}
$[\sigma_T]$ - Yield Strength (depend of alloy)	85 (80 - 120)	N/mm^2

This nonuniform load distribution on the inner porous metal bearing model surface is shown in Fig.4. with rotation direction and lines that present different radial load values.

Caused by friction, the temperature field of porous metal bearing, homogeneous and isotropic material is defined by energy equation in polar coordinates:

$$\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{1}{r^2}\frac{\partial^2 T}{\partial \theta^2}+\frac{\partial^2 T}{\partial z^2}=0\,, \quad (10)$$

which defines thermics flux through elementary bearing surface [7]:

$$\dot{q}_i = p\,\upsilon\,\mu=\frac{3\upsilon^2\eta}{rc^2}\left[\frac{\varepsilon\sin\theta}{(1+\varepsilon\cos\theta)^3+12\Psi}\right]\cdot \left(\frac{b^2}{4}-z^2\right)\mu\ +p_b\,\upsilon\,\mu\,. \quad (11)$$

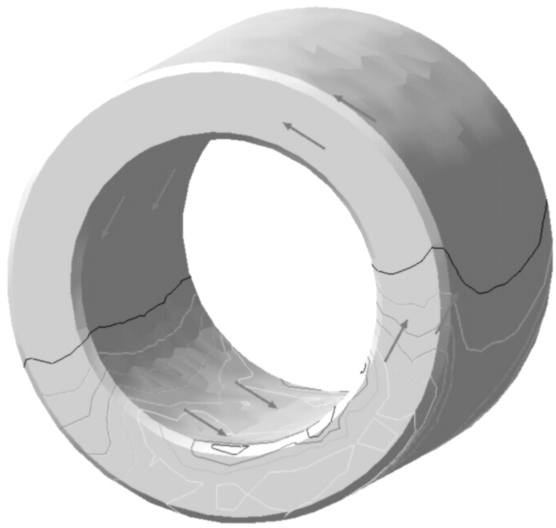

Figure 4. Load distribution from radial force

Starting from the solution of this thermal flux equation and also using experimental results [8], temperature field for porous metal bearing (Fig.5) is defined.

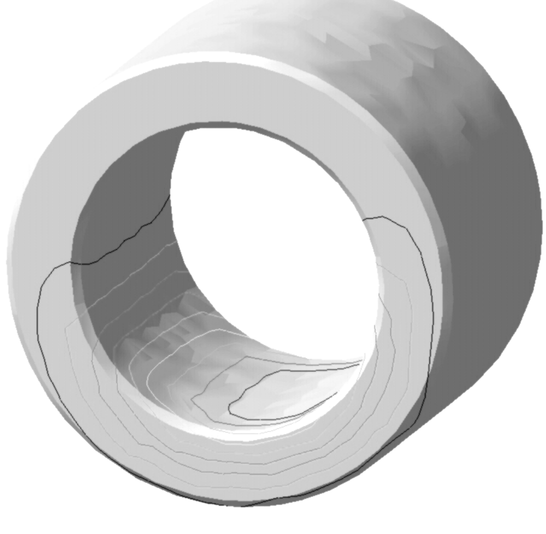

Figure 5. Temperature field of porous metal bearing

2.2. Processing or calculation phase

To calculate correct stress values in all bearing model nodes, elastic balance equations are to be defined. Equations that connect stress and external load values in a model node (x, y, z), can be written in the matrix form:

$$[B]^T \{\sigma\} + \{F\} = 0 , \tag{12}$$

where $[B]^T$ is transponded matrix of differential operators. Partial differentiation of stress vector $\{\sigma\}$ gives equations system that is to be solved:

$$\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} + X_F = 0 , \tag{13}$$

$$\frac{\partial \tau_{yx}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} + Y_F = 0 , \tag{14}$$

$$\frac{\partial \tau_{zx}}{\partial x} + \frac{\partial \tau_{zy}}{\partial y} + \frac{\partial \sigma_{zz}}{\partial z} + Z_F = 0 , \tag{15}$$

where X_F, Y_F and Z_F are external forces components. Because of symmetric stress tensor, it is: $\tau_{ij} = \tau_{ji}$ $\tau_{ij} = \tau_{ji}$, ($i, j = x, y, z$).

Processing phase of calculation of these equations could take a lot of time, depending on finite elements number and how complex external load is. Over the past years this problem can be solved in a reasonably short time regarding new computers and software possibilities. Calculation of this problem is done using structure analysis modulus of software CATIA V5 R11. In this case of complex bearing load, but relative low number of finite elements, the calculation process measured in dozens of minutes.

2.3. Post processing or results analysis phase

The stress values calculation in most of FEM software is based on using Huber, Misses and Hencky hypothesis about potential energy of deformations where:

$$\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - (\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_3\sigma_1) \le [\sigma]^2 . \tag{16}$$

After getting stress and deformation values, analysis is to be made,which is of great importance for making proper optimization model.

The FEM application makes possible to analyze every component separately is influence of complex load, such as in the case of porous metal bearing are radial force, sliding friction force and nonuniform temperature field. But the main advantage of FEM is to have a summary effect of all these components that make a complex load. This summary stress values on bearing volume is given here (Fig.6.), where one can see significant influence of temperature load component compared with stresses made by radial force operating.

A very important parameter for bearing is also changing of clearance caused by its complex load. These values are shown in Fig.7., where the maximum displacement node at bearing model can be seen.

The shown results give very important conclusion about taking elastic deformations in account in calculation based on hydrodynamic lubrication theory. This means that porous metal bearing, even at points with maximum displacement values (4.3μm) could not reach mounting clearance value during its work under operational bearing life conditions. This result demonstrate the evidence of safety journal porous metal bearing work, also with elastic deformations taking in account, which prevents it from shaft contact in whole working life.

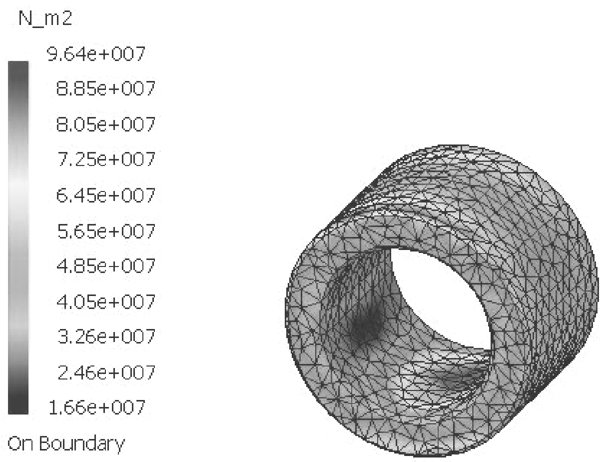

Figure 6. Summary von Misses stress values

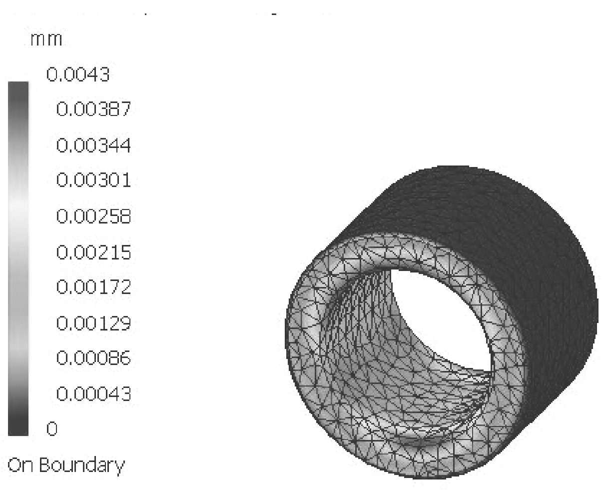

Figure 7. Displacement values of FEM model

3. OPTIMIZATION MODEL DEFINITION

To define every optimum design problem, one should start with identification of variable vector components, thereafter comes the objective function choice and it is also to set a task of necessitous constrains.

In this optimization model definition for porous metal bearing based on the results from structural analysis, a variable vector should have main bearing dimensions to get optimal geometric parameters [9].

Besides dimensions, yield strength is taken here as variable that represents the influence of bearing material. This variable vector can be written as follows:

$$\overline{\boldsymbol{x}} = (x_1, x_2, x_3, x_4) = (R_s, H, b, [\sigma_T]) \,, \quad (17)$$

where $R_s = D/2$ is outer bearing radius, $H = (D-d)/2 = R_s - r$ -bearing wall thickness, b- bearing length and $[\sigma_T]$ - yield strength of bearing bronze alloy.

In this model some parameters are taken that are constant in optimization process, such as radial bearing load $W = 550$ N, number of rotations $n = 1350$ min^{-1}, and also "*pv*" characteristic values measured by own experiments.

For correct operation of porous metal bearing in elastohydrodynamic conditions, the values of deformations are very important. In structural analysis elastic deformations and potential energy of deformation were clearly correlated, which was the reason for taking this energy as objective function:

$$\min E_{\text{def}}(\overline{\boldsymbol{x}}) = \min E_{\text{def}}\left(R, H, b, [\sigma_T]\right). \quad (18)$$

The main supposition in stress analysis was that deformations are only elastic, which makes constraint:

$$g_1(\overline{\boldsymbol{x}}) = [\sigma_T] - \sigma_i > 0 \,, \quad (19)$$

where $\sigma_i = \sigma_{\text{Mises}}$ is maximal stress value according to the Misses hypothesis.

Admissible set of solutions D for this constrained optimization problem:

$$\min_{\overline{x} \in D} E_{\text{def}}(\overline{\boldsymbol{x}}) = \min_{\overline{x} \in D} E_{\text{def}}(R, H, b, [\sigma_T]) \,, \quad (20)$$

can be now written in the form of equation:

$$D_{\text{opt}} = \left\{ \overline{\boldsymbol{x}} \in R^n \mid g_1(\overline{\boldsymbol{x}}) > 0 \right\}. \quad (21)$$

4. SOLUTION OF THE PROBLEM

Searching for the solution of defined optimization problem is the process of searching for optimal value of variables vector in the frame of admissible solution set D_{opt}. Additional problem in this structural optimization is a fact that every testing for potential solution of variables vector is to make a completely new structural analysis with calculation of all stresses and deformation energy values. This complex structural optimization problem was solved using modulus for one-dimensional optimization in CATIA V5 software. Besides standard gradient method, this tool can use Simulated-annealing method (SA) [10]. As a relative new stohastic method, SA has been commonly in use over the last years for solving constrained nonlinear optimization problems. The main advantage of using SA is the possibility for missing local minimum and also in case of complex optimization problems the objective function that can have any mathematic form makes no problem in finding optimal solution [11].

Based on the results of optimization process, Table 2. shows variables vector values and values of objective function. Because of easier analysis and compison the starting case of bearing is given here, whose stresses and deformations were analyzed before optimization process. The next row shows values of calculated optimal bearing solution that can be compared with starting. By comparing these one can conclude that:

Optimal (minimum) objective function gives 5% reduced value of potential deformation energy compared with the starting case.

As for optimal values of geometric variables, it is to say that all bearing dimensions are a little bit smaller.

If analyzed variable represents bearing material, optimal values show that bronze alloy is to be chosen, which has Yield Strength that satisfied constraint.

Table 2. Variable vector and objective values

Model	Variables				Objective function
	$x_1 = R_s$	$x_2 = H$	$x_3 = b$	$x_4 = [\sigma_T]$	$\min E_{\text{def}}$
	mm	mm	mm	N/mm^2	J
starting	15	5	20	85	0,3213
optimum	14,48	4,82	19,61	100	0,304

Here, it can be said that definition of bearing optimization model can take minimum value of Misses stresses as the objective function instead of potential deformation energy, but this would give similar or the same vector for optimum solution according to the hypothesis for stresses values calculation in structural analysis.

5. CORRELATION ANALYSIS

This analysis is conducted to complete the results of optimization shown in Table 2., where it can not be seen how variables are correlated and their influence on deformation energy, value of stresses or, for example, bearing mass as an external parameter [5].

Compared with other variables, it is interesting to show the influence of bearing wall thickness on calculated Misses stress. Average Misses stress values, its maximum and minimum response with dependence of wall thickness are shown in Fig.8.

Besides this dependence, in Fig.9. is presented the influence of outer bearing radius on Misses stress values calculated in structural analysis.

As a result of this analysis, it is clear that bearing dimensions have no strict influence on Misses stress values, but it is easy to see that wall thickness has a rather small influence on stress. A significant influence has outer radius of bearing, where minimum stress value is reached for $R_s = 13$ mm.

Because of using SA as a stochastic method in optimization process, in the above Fig. 8. and Fig. 9., besides average, are also given responses from minimum to maximum stresses. This means that stress has a normal distribution in admissible set of solutions, where over 99% of values are in response between shown max. and min. lines.

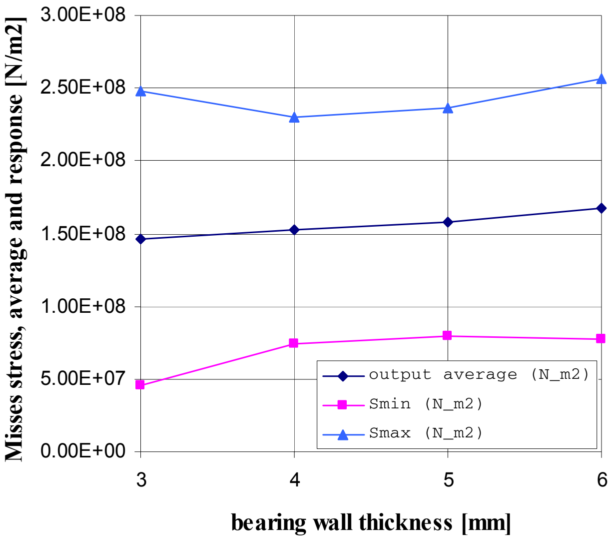

Figure 8. Stress dependence of the wall thickness

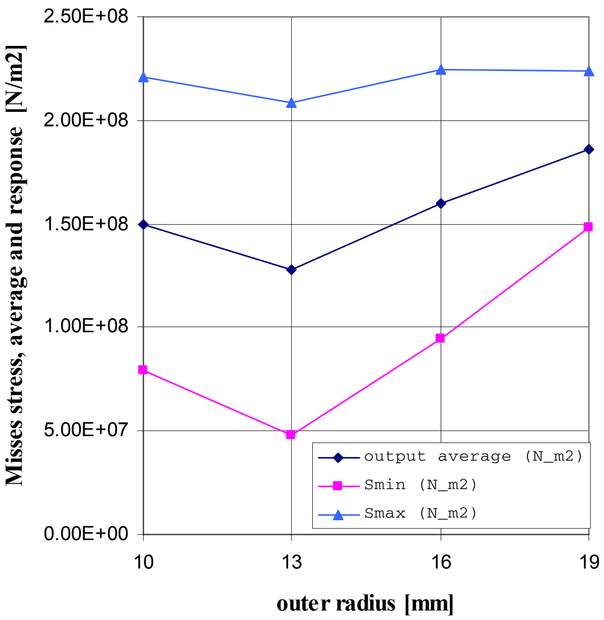

Figure 9. Stress dependence of outer diameter

After this correlation analysis between stress and geometric parameters, in case of structural optimization based on stress and deformation FEM analysis, the influence of finite element dimension on calculated results can be also analyzed. Preprocessing phase explains and in Fig. 2 gives linear tetrahedron as a finite element for bearing stress analysis. In addition, Fig. 10. shows that smaller size of finite element fills much better bearing model volume that makes some higher stress values.

Mean slope of the lines in correlation analysis could be also a useful parameter for making some conclusion about the influence of some variables in admissible solution set. Such example could be the slope of the line in tetrahedron size responses (Fig.10.), which shows that influence on Misses stress value is lowest for finite element with dimensions between 1,5 and 2mm. That fact proves a proper choice of finite element size (1.88mm) in preprocessing phase of porous bearing structural analysis and also confirms very good ability of SA method applying in optimization problems solving against its stochastic character.

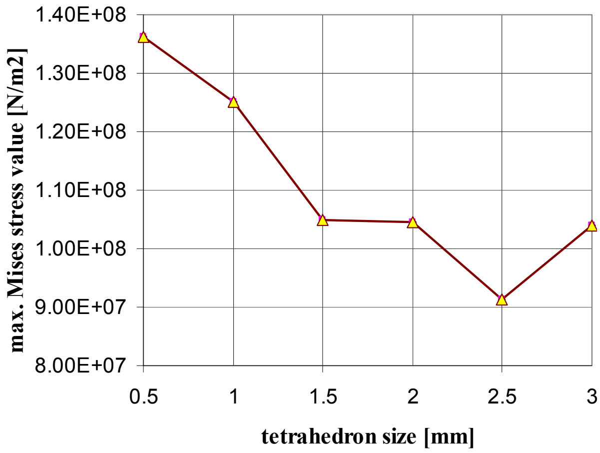

Figure 10. Influence of tetrahedron size on stress

6. CONCLUSION

The main idea of this paper was to make a contribution to porous metal bearing research and to present qualitative new approach to optimization of bearings. This approach has some advantages and with presented results it could be concluded the following:

- Structural analysis using FEM with stresses and elastic deformation calculation gives additional possibilities in approach to make an elastohydrodynamic model of porous metal bearing.
- Presented optimization model based on structural analysis, resulted in variables vector optimal values, where minimum deformation energy is used as the main objective function in optimization process.
- This structural optimization problem with stresses analysis is solved in CATIA V5 software tool using “Simulated annealing” (SA) method with advantages that allow its applying for every objective function form in optimization.
- Presented correlation analysis makes possible a qualitative new access to optimization, where apart from interaction analysis, the influence of variables on some external parameters could be analyzed.
- The finite element size analysis and its influence on bearing characteristics makes possible some corrections in the starting phase of structural optimization. This makes choosing the right finite element size much easier in achieving the lowest possible error, where SA method applying gives its own contribution.

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NOMENCLATURE

$[B]$	- matrix of differential operators
$[B]^T$	- transponded matrix of diff. operators
b	- bearing length
c	- radial clearance
D	- outer diameter of bearing
$[D]$	- matrix of elasticity
d	- inner bearing diameter (shaft diameter)
D_{opt}	- domain of optimum design solutions
E	- Young elasticity modulus
E_{def}	- energy of deformations
$\{F\}$	- matrix of load in nodes
G	- slith modulus
$g(\bar{x})<0$	- unequality functional constraints
H	- bearing wall thickness
$h(\bar{x})=0$	- equality functional constraints
$[K]$	- matrix of stiffness for finite elements
n	- number of shaft rotations
p	- fluid pressure (lubricants leyer)
p_{b}	- barometric pressure
R	- inner bearing radius
R	- shaft radius
R_{S}	- outer bearing radius
υ	- sliding velocity
W	- radial bearing load
X_F	- external force component in x direction
$\bar{x}$	- variables vector in optimization
Y_F	- external force component in y direction
Z_F	- external force component in z direction

Greek symbols

α_t	- Thermal expansion coeffitient
γ	- angle deformation
$\{\delta\}$	- matrix of nodes displacement
ε	- relative excetricity
ϵ	- linear deformation
$\{\epsilon\}$	- matrix of deformations
ρ	- density of fluid (lubricant)
ρ_l	- density of porous bearing material
η	- dinamic viskosity of fluid
Ψ	- constructive parameter of bearing
Φ	- permeability of porous bearing material
μ	- friction coefficient
θ	- angle coordinate
σ	- normal stress
$\sigma_1, \sigma_2, \text{i } \sigma_3$	- stresses values in main directins
$[\sigma_T]$	- yield stregth of bearing material
σ_{Mises}	- stress calculated by Misses hypothesis
σ_{ij}	- stresses in directins $i,j = x,y,z$
τ	- shear stress
τ_{ij}	- shear stresses in directions $i,j = x,y,z$
ν	- kinematics viskosity of fluid
ν_p	- Poasons coefficient

СТРУКТУРАЛНА ОПТИМИЗАЦИЈА ПОРОЗНИХ РАДИЈАЛНИХ КЛИЗНИХ ЛЕЖАЈА

Александар Маринковић

Производња и истраживање самоподмазујућих клизних лежаја су у сталној експанзији због своје особине да су погодна за одржавање и имају дуг радни век. Ово је вероватно веома важан разлог за њихову уобичајену употребу код већине савремених машина и механизама, где порозни клизни лежаји заузимају лидерску позицију. Са новим методама симулације и софтверским алатима могуће је сачинити квалитативне анализе понашања клизних лежаја, узимајући у обзир њихове еластичне деформације. У овом раду представљена је структурална оптимизација радијалних порозних клизних лежаја који су сложено оптерећени. Као

оптерећење на унутрашњој површини порозног клизног лежаја узета је расподелом притиска израчуната по хидродинамичкој теорији подмазивања. Поред тога постоји и сила трења клизања, као и неравномерна расподела температура по запремини лежаја, које такође треба узети у обзир. Структурална анализа је урађена за свако од наведених оптерећења појединачно, као и за сложено оптерећење ових лежаја. Анализа је обављена методом коначних елемената (МКЕ) у модулу за структуралну анализу софтвера *CATIA V5R11*. На основу резултата ове анализе у другом делу рада је дата параметарска оптимизација порозног клизног лежаја, узимајући у обзир еластичне деформације чауре лежаја. Симулације, анализе и оптимизација, које су реализоване помоћу *CATIA V5R11* су у овом раду представљене и илустроване одговарајућим сликама и дијаграмима.