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JOURNAL BEARING OPTIMIZATION FOR MINIMUM LUBRICANT VISCOSITY

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ABSTRACT

In this paper the optimum geometry of journal bearings is determined for the minimum possible viscosity of the lubricant. During the investigations the basic equation of the THD (Thermo- Hydrodynamic) state of hydrodynamic journal bearings is solved by using the finite difference technique, while for the optimization the RVA (Random Virus Algorithm) is used. Design variables are the coordinates of the 40 keypoints selected for creating the finite difference mesh. All the operational and geometry limits are included as implicit constraints. As the result of the optimization process, the lubricant viscosity can be considerably decreased compared to the starting design, this makes possible to apply water as lubricant in the bearing. This will decrease the lubricant cost by more than 95%, which is a very important achievement.

KEYWORDS

Journal bearing, minimum viscosity of lubricant, multidisciplinary optimization, evolutionary RVA algorithm.

INTRODUCTION

Thermo- hydrodynamic sliding and journal bearings are commonly used in many fields of mechanical and energy engineering. The lubricant is a very important component in these bearings. In many cases oil is used as lubricant, but nowadays one can find other materials too, used as lubricants (metals, water, air, gases, grease, etc.). The most important characteristics of the lubricant in point of view of the operational parameters of the journal bearings is the viscosity. Oils and greases provide relatively high viscosity but they are expensive comparing to some smaller viscosity lubricants (water, gas, air) which could be cheaper. This thinking leads to application of the methods of Multidisciplinary Optimization (MDO) for journal bearing optimization with the lubricant viscosity as objective function to be minimized. If the necessary lubricant viscosity for the appropriate operation of the bearing can be decreased enough, this result can give the possibility to use smaller viscosity (and cheaper) lubricant, which will decrease considerably the lubricant costs. Changing the lubricant material from oil to air or water could be very useful from environmental protection point of view too. In some fields of life (agriculture, food industry, water plants or pumps, or for some other industrial applications)

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water is very close or maybe it is a part of the working process so it will be easy to provide or in some cases it will be not so bad if some drops of the lubricant (water) will go into the processed material (in this case it must be clean enough) so the sealing could be simpler or cheaper too.
Finding the optimum geometry of journal bearings for minimum lubricant viscosity needs optimization techniques, while the effects of the temperature (THD state, Thermo- Hydrodynamic State) will enlarge the analysis process into a multiphysics or multidisciplinary analysis process. Therefore the whole optimization process will be an example of Multiphysics Optimization or Multidisciplinary Optimization (MDO). The disciplines involved in this complex process are: fluid flow, heat transfer, solid mechanics, elasticity and tribology. The complexity of these analysis processes makes it necessary to use several numerical methods (finite difference, finite element), which can sometimes be time consuming and takes a large amount of computing capacity. Therefore very efficient and quick optimization algorithms are needed for the Multidisciplinary Optimization of hydrodynamic bearings, in order to avoid overwhelming calculations and excessively long calculation times.
During the last 2-3 decades, evolutionary type optimization algorithms have provided the best ways to solve MDO problems, because of their efficiency, robustness and quick convergence. The basic idea of these algorithms came from the study of the behavior and reproduction of several natural systems such us genetic engineering (Genetic Algorithm GA [2]), evolution of biological populations (Evolutionary Programming EP, or Evolutionary Strategies ES), Reproduction of Bacteria (Bacterial Foraging Algorithm, BFA), behavior of natural swarms (Particle Swarm Optimization, PSO , or Virus-Evolutionary Particle Swarm Optimization VEPSO), behavior of animal colonies (Ant Colony Algorithm, ACA), or behavior and reproduction of viruses (evolutionary type Random Virus Algorithm, RVA [6]).
In this paper the Random Virus Algorithm (RVA) is used for the optimization of hydrodynamic journal bearings. For the numerical analysis of the hydrodynamic bearings in each step the finite difference technique is used. The temperature depedence of the lubricant characteristics (density, viscosity) is taken into consideration by iterative steps during the numerical solution of the governing partial differential equation. The objective function of the optimization is the lubricant viscosity needed for the apropriate operation and good load carrying capacity of the bearing. During the optimization the minimum of the objective function is sought.
As the result of the optimization the lubricant viscosity is decreased in a so great extent, that instead of oil lubricant water can be used. This will decrease the lubricant costs by more than 95% and it can have very important environmental protection advantages, too.
As further development of this work, the multidisciplinary optimization of gear tooth geometry for higher safety against seizure will be investigated, applying the presented process.

SOLUTION OF THE THD STATE OF THE JOURNAL BEARINGS

The applied numerical method is applicable to any problem that can be described by linear partial differential equations. In this work it is used for solving the pressure distribution *p(x,z)* in the fluid film of hydrodynamic journal bearings, for a given gap shape function *h(x,z)* . The governing equation of this problem is the Reynolds equation:

$$\frac{\partial}{\partial x}\left(h^3\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial z}\left(h^3\frac{\partial p}{\partial z}\right)-6\eta U\frac{\partial h}{\partial x}-12\eta\frac{\partial h}{\partial t}=0 \quad . \qquad (1)$$

In Equation (1) the relative velocity of the sliding surfaces is denoted by *U*, and *η* means the absolute viscosity of the lubricant.
Equation (1) can be written into matrix form, after the discretization of the fluid film domain between the sliding surfaces, by using finite differences, as shown in equation (2). The vector **p** collects the nodal values of the pressure function, and elements of matrix **K** depend on the nodal values of the gap shape function:

$$\mathbf{Kp} + \mathbf{g} = \mathbf{0} \ . \qquad (2)$$

In case of a finite difference mesh having *u X v* nodes, the matrix **K** will have a bandwidth of *2v – 3*, after the applications of the boundary conditions.
The density and the viscosity of the lubricant is the function of the operating temperature of the bearing. This is taken into account by an iteration during this numerical solution. At the beginning, an approximate temperature is supposed and the equation is solved with characteristics calculated for this temperature. On the basis of the results, new and more accurate temperature value can be determined. The whole calculation will be repeated with lubricant characteristics calculated with this new temperature value. Several trial- calculations and experiences show that after three or four iteration cycles the difference between the temperature values before and after a calculation step will be smaller than 1^{o}C, which is enough accurate for the further calculations. The elastic deformation of the shaft and housing could be checked by finite element model after the solution (quasi- TEHD state), this could be effective if these deformations are small comparing to the gap size (for example in case of steel shaft and steel bushing).
Once we have the solution of this process for the nodal values of the pressure function, the load carrying capacity of the surface pairs F_n can be calculated by numerical integration, using the characteristic sizes (*r, R, b,* h_o*, e*) of the bearing.

$$F_1=\int_{\varphi=-(\beta-\varphi_1)}^{\varphi_1}\int_{z=-\frac{b}{2}}^{b/2} p\,r\,d\varphi\,dz\cos\varphi \ ; \qquad F_2=\int_{\varphi=-(\beta-\varphi_1)}^{\varphi_1}\int_{z=-\frac{b}{2}}^{b/2} p\,r\,d\varphi\,dz\sin\varphi \ ;$$

$$F_n=\sqrt{F_1^2+F_2^2} \ . \qquad (3)$$

The friction force, which is the force needed for the relative motion between the shaft and bushing can be determined as follows:

$$F_f = \int_{x=-r(\beta-\varphi_1)}^{r\varphi_1} \int_{z=-\frac{b}{2}}^{b/2} \left(\frac{1}{2} \frac{\partial p}{\partial x} h - \eta \frac{r\omega}{h} \right) dx dz \tag{4}$$

In equation (4) the angular velocity $\omega = 2\,\Pi\, n$, if the unit of the angular velocity is radians per seconds and the n rotation speed is in rotations per seconds. The frictional coefficient μ can be calculated as $\mu = F_f / F_n$. Lubrication angle β together with the angle φ mark a general position of the gap function $h(\varphi)$.

$$h(\varphi) = R - r - e\cos\varphi \tag{5}$$

This calculation method has been verified and compared to the analytical solutions for infinite width bearings given by Szota and Döbröczöni [3], optimized for maximum load carrying capacity, and good agreement was found between the theoretical and numerical results [5]. Another verification of the method was in the case of finite sliding bearings [4], [5] where the results of this finite difference based code were compared with those calculated by the ANSYS- FLUENT [1] program system and once again good agreement was detected.

THE RVA OPTIMIZATION ALGORITHM

The design variables are the nodal coordinates of the finite difference mesh keypoints. For the meshing 40 key nodes are used with variable coordinates (these are the optimization variables) and remaining nodes are placed depending on the keypoints in order to make higher density mesh. For the optimization problem presented here the objective function is the lubricant viscosity η which is to be minimized. Size constraints: 0 [mm] < r < 500 [mm] , 0 [mm] < R < 500 [mm] , 0 [mm] < e < 10 [mm]. Implicit constraints: the pressure function should fulfill the Reynolds equation (1) of hydrodynamic surface pairs; the shaft diameter should be higher than the minimum required diameter given in equation (6); the average pressure in the fluid film should be smaller than the maximum permissible average pressure (2 MPa) as it is shown in equation (6); and the minimum gap distance h_o should be higher than the sum of the maximum roughness of the surfaces plus the elastic deformations of the surfaces. Maximum permissible operational temperature is 80 ^{o}C for oil and 40 ^{o}C for other lubricant (e.g. water).

$$r \geq 0.5\sqrt{\frac{F}{\bar{p}_{adm} b/d}} \quad , \qquad h_0 \geq 4.5(R_{a1} + R_{a2}) \quad , \qquad \bar{p} \leq \bar{p}_{adm} \quad . \tag{6}$$

According to the logic of the RVA optimization algorithm, the first step is to create the first (or starting) population of the possible solutions fulfilling the constraints. Once the starting population has been generated, each member of the population will reproduce, creating three new members each. This process is stronger than a nuclear explosion, so in the remaining part of the optimization the selection of the best members and elimination of members without good enough objective function

values will be very important. At least 60% of the new and of the total members should be eliminated after each population in order to avoid overwhelming calculations. The members that survive this strict selection procedure will give the second population. The programming of the RVA algorithm is very simple, easy to carry out in any programming language or in macro languages of finite element program systems, if available.
This procedure will continue until the pre-defined optimum conditions are fulfilled. Several benchmark problem runs and numerical experiments have shown that the algorithm is very efficient: in the optimization problem investigated in this work 5 populations were enough to find the optimum. The total computation time required for a complete run was 23 minutes on an Intel core i5 desktop computer.
The jth population: $P_j = \{x_i\}_j$; the reproduction formula:

$$y_k = x_k + R_k q^* (up_i - lw_i) \quad (7)$$

Where y_k means the k^{th} variable value of the new member, q* is the spreading parameter, and R_k is a random number between 0 and 1, simulating the possibility of random mutations. Setting the spreading parameter properly is also very important, because it can have a considerable effect on the efficiency of the algorithm. This needs a great deal of experimentation and unique fine-tuning work for each optimization problem. For this optimization process the best value for the spreading parameter was 0.65 in the first three populations and 0.29 afterwards.
If the maximum number of iterations is reached without fulfilling the convergence criteria, it means that the search procedure needs more iterations and so the optimization is stopped, but during the results display a warning will say that there is a danger of a local optimum and possibly a new run will be necessary with other parameters or with a higher maximum number of iterations permitted.

RESULTS OF THE OPTIMIZATION

As numerical example a hydrodynamic journal bearing of an electric generator has been optimized by using the multidisciplinary optimization (MDO) procedure described in the section 2 and 3.
Table I shows all the important parameters of the bearing, after calculating the most important sizes of the bearing from the optimal design variables. In the table it can be seen that important achievement was made in the objective function value as results of the optimization:

Table I.
Optimization results for two different objective functions

	r [mm]	R [mm]	e [mm]	μ	F_n [N]	T [°C]	$\bar{p}$ [MPa]	Decrease in η [%]	h_o [μm]	Joint (ISO)
Starting	80	80,130	0,0799	0,00305	31400	74,95	0,943	-	50,54	H7/a9
Min. η	65	65,052	0,0501	0,00065	31400	29,65	1,43	40	20,42	H7/a9

CONCLUSIONS

THD state journal bearings are optimized for minimum necessary lubricant viscosity. The design variables are the keynodes selected for the finite difference mesh during the numerical solution of the Reynolds equation. The dependence of the lubricant characteristics from the temperature is taken into consideration by an iteration for the operation temperature.

For the optimization the RVA evolutionary type optimization algorithm was applied and the optimization process can be treated as Multidisciplinary Optimization example.

The most important achievement of the optimization is that the lubrication material of the bearing can be decreased from oil to water. This could decrease the lubricant cost by more than 95% and can provide important environmental protection advantages.

Using the table I designers and users of the bearings can find how to redesign the bearing in order to realize the water lubrication state having all the most important operational characteristics of the bearing (load carrying capacity and friction coefficient) remain the same or slightly improved.

Further investigations will be made for the optimization of gear tooth for minimum danger of seizure.

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