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NUMERICAL SIMULATION OF SLIDING WEAR FOR SPHERICAL PLAIN BEARINGS WITH SELF-LUBRICATING FABRIC LINER[1]

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Abstract

Based on the thermo-mechanical finite element analysis method, a thermal wear simulation program was designed for the wear properties analysis of spherical plain bearing with self-lubricating fabric liner. In the program, the classical Archard wear model was applied to analyze the dynamical wear process of the bearing, and ABAQUS scripting interface was used to simulate the progressive accumulation of wear between contact surfaces. The position of maximum wear depth occurs at the central contact region, this is close agreement with the test results. And the relative error of the maximum wear depth between the FEA prediction and experimental results is little than 10%. It is shown that the complex nonlinear wear process can be simulated with a series of discrete quasi static models and the wear simulation program could be used to analyze the practical mechanical and tribological properties of the spherical plain bearings.

Keywords: Spherical plain bearing; Finite element method (FEM); Wear Simulation; Thermal analysis

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1 INTRODUCTION

The diversity and complexity of wear phenomenon makes it difficult to accurately predict wear life of mechanical parts. The most confident knowledge about the friction pair tribological behaviour can be achieved by taking lots of wear experiments. However, experimental exploration is not only costly, but also not satisfactory when it comes to practical problems of uneven load distribution as well as changeable load, such as wear life span of spherical plain bearing with woven fabric liner.

With the rapid development of computer technology and tribology in the past 20 years, "calculation tribology" has become a branch of tribology(1,2) and demonstrated its strong vitality. FEM is widely used to simulate wear progress of mechanical parts. Hegadekatte, Huber and Kraft (3-5) and Hagadekatte et al.(6) calculated wear of the micro-mechanical devices based on finite element simulation. The experimental results were in good accordance with the simulation results. Nam Ho Kim et al.(7) simulated a block-on-ring experiment and achieved good results. And FEM was used to simulate fretting wear as well as the evolution of fretting variables with the number of wear cycles in a cylinder on flat configuration both made of Super CMV, a hardened steel alloy.(8)

The spherical plain bearings with self-lubricating can achieve self-lubrication and long life due to their own structural characteristics, so they have been widely used in aerospace, tank cannon gun system, and etc. Figure 1 gives the structure schematic diagram of this type bearing. It is composed of an inner ring with a spherical outside surface and an outer ring which has an inner sphere. Woven fabric liner is pasted on the inner surface of the outer ring. The main failure form of this type bearing is the wear of the woven fabric liner.

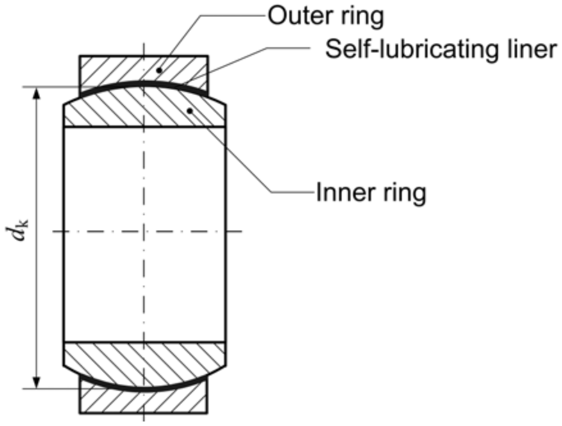

Figure 1. Schematic of spherical plain bearing with self-lubricating.

Based on the thermo-mechanical finite element analysis, a numerical simulation forecasting method was proposed to solve sliding wear problem of the spherical plain bearing with self-lubricating fabric liner in this paper.

2 ARCHARD WEAR MODEL

The wear process can be treated as a dynamic process, depending on many parameters and the prediction of that process as an initial value problem. The most frequently used model is based on the Archard's wear law. Archard's equation for sliding wear is normally expressed as:(9)

$$\frac{V}{s} = k \cdot \frac{F_N}{H} . \qquad (1)$$

Where V is the wear volume, s is the sliding distance, F_N is the normal load, H is the hardness of the worn surface and k is the dimensionless wear rate. In order to simulate the evolution of the contact surface profiles with wear cycles, it is necessary to determine the wear depth at each contact node of the finite element model. Therefore, for an infinitesimally small apparent contact area, ΔA, the increment of wear depth, dh^w, associated with an increment of sliding distance, ds, is determined. This can be obtained by applying (1) locally to the area ΔA and for the increment of sliding distance, ds:

$$\frac{dV}{ds} = k \cdot \frac{F_N}{H} . \qquad (2)$$

Then, dividing both sides by ΔA, the following equation is obtained:

$$\frac{dV}{ds \cdot \Delta A} = k \cdot \frac{F_N}{H \cdot \Delta A} . \qquad (3)$$

The $F_N/\Delta A$ term is the local contact pressure, p, while $dV/\Delta A$ is the required increment of local wear depth, dh^w. The following equation is thus obtained for the prediction of the increment of local wear depth:

$$\frac{dh^w}{ds} = k_D \cdot p . \qquad (4)$$

Where k/H is replaced here by k_D, the dimensional wear rate. Thus, the total wear depth h^w of every element between the contact surfaces could be formulated as

$$h^w = \int k_D \cdot p \cdot ds . \qquad (5)$$

3 FINITE ELEMENT MODELING AND SIMULATION

3.1 Finite Element Modeling

The spherical plain bearing shown in Figure1 was taken as an example of wear simulation. The outer ring and inner ring of the bearing were made of aluminum alloy, and the self-lubricating liner was woven fabric liner. For simulating the experimental conditions of the bearing system (Figure 2), a test ring and shaft were also implemented (Figure 3), both of which were rigid body. Since analytical method was not available to analyze spherical plain bearing problems, finite element analysis code ABAQUS was used to solve the non-linear contact problem. The strength of finite element analysis in making wear predictions is its ability to accurately consider both the variation of the contact pressure and the progressive change of the surface geometry caused by material removal in complex three-dimensional components. Cao, Shen and Li(10) showed that the maximum contact pressure between inner ring and outer ring occurred on the axial cross-section, which was the intersection plane between XOY plane and the bearing system (Figure 4). Therefore, the maximum wear depth would occur on the same section in terms of Archard's wear model. In order to simplify calculations, the two dimensional finite element wear simulation model of the spherical plain bearing was established, shown in Figure 4.

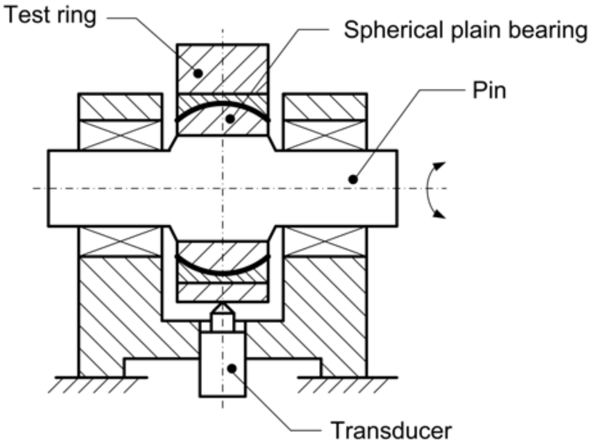

Figure 2. Schematic of bearing test system.

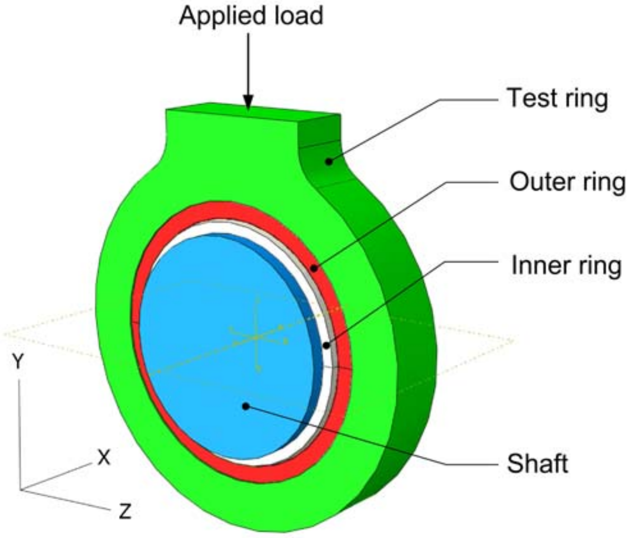

Figure 3. 3D Model of bearing test system.

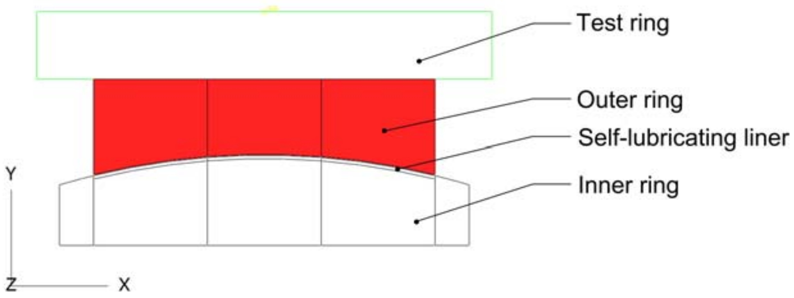

Figure 4. Axial cross-section model of spherical plain bearing.

3.2 Wear Simulation Routine

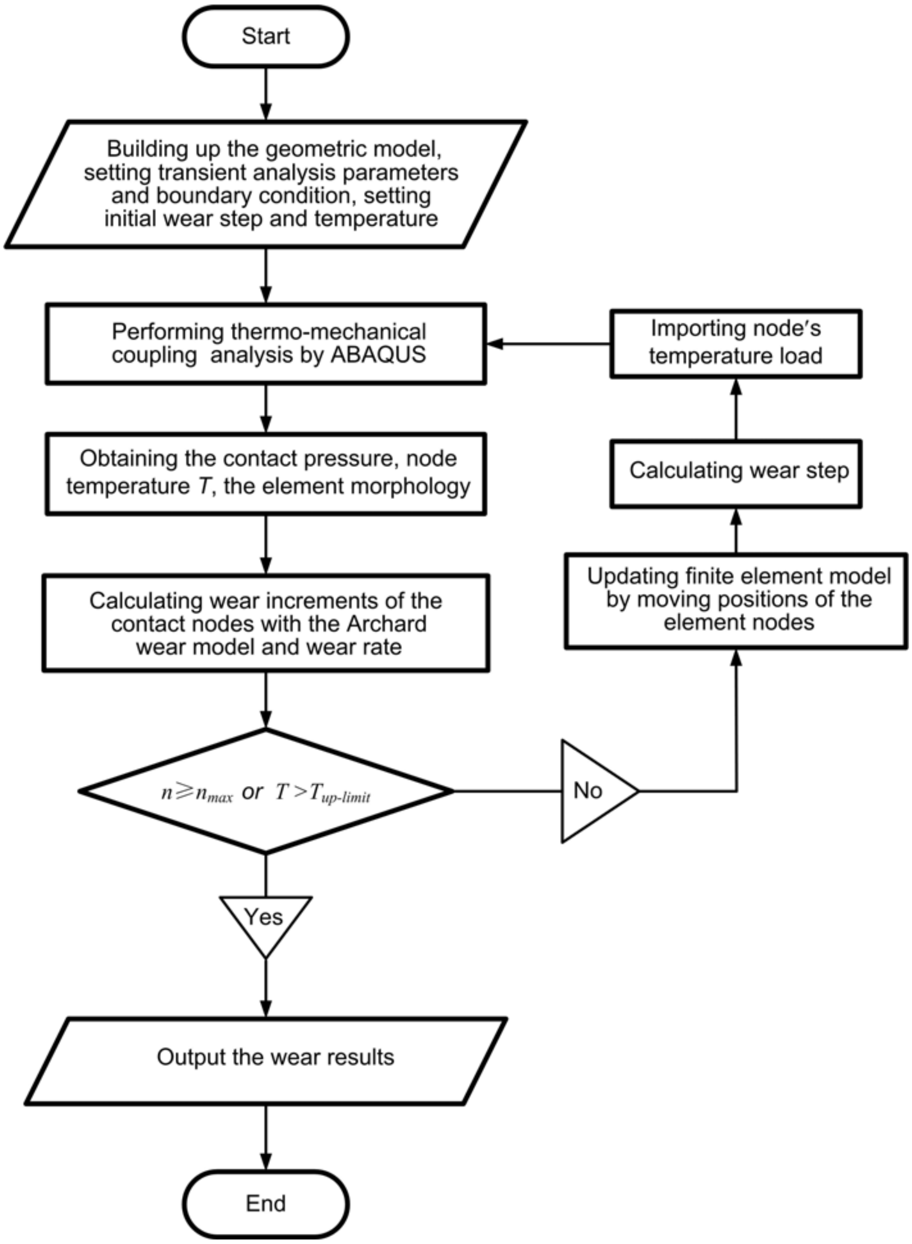

Figure 5. Wear simulation flow chart of spherical plain bearing.

The flow chart of the finite element wear simulation procedure, consisting of a series of thermo-mechanical coupled solution steps, was shown in Figure 5. The ABAQUS scripting interface was introduced to carry out the wear simulation program.

The initial parameters given defined the model geometry, loads, constraints and wear model parameters along with the element and material data. The heat flux was obtained from the three-dimensional thermo-mechanical analysis model of the bearing system.(10) Special subroutines were developed for every configuration to generate the FE model and define the loads and constraints automatically. Simulation of wear began with the solution of the general contact problem using ABAQUS. Then, Archard's wear model was implemented to calculate linear wear. According the wear depth, the FE model was updated. If oscillating cycles $n \geq n_{max}$ (predetermined maximum oscillating cycles) or the node temperature T exceeds the maximum allowable temperature $T_{up\text{-}limit}$, the cycle of calculation would be stopped, otherwise it would go to the next iteration process until the above two conditions are satisfied.

3.3 Re-meshing Technology and Proper Wear Step

To analyze dynamical wear process of the bearing, the entire wear distance was divided into many wear steps. At the same time, a proper re-meshing technology and selected wear step should be used to increase the calculation efficiency and precision.

Since element distortion is a key factor that affects accuracy of the results, re-meshing technology must be considered during the process. In order to simulate wear of the contact surface, coordinate position of the nodes must be changed, because the calculating mesh on the surface is worn out. Whereas, changing positions of boundary nodes may yield inaccurate sensitivity results or a distorted finite element mesh, and thus fail in achieving an optimal solution. Thus, it is necessary to re-mesh the model after each cycle. Boundary displacement method (BDM) of the design sensitivity analysis (DSA) is widely employed to update the finite element mesh for FEA. Before using BDM, displacements of each element node must be calculated. Then, the displacements are used to update finite element model.

Table 1. Adaptive wear step

Oscillating Cycles n	Wear Step
$n < 200$	2 cycles
$200 \leq n < 500$	50 cycles
$500 \leq n < 5000$	100 cycles
$5000 \leq n < 10000$	500 cycles
$n \geq 10000$	1000 cycles

The integration wear step is another parameter regarding the calculation efficiency and the reliability of simulation results. The entire wear distance was divided into finite wear steps. Too long wear step causes erratic results and possibly the un-convergence of FEA procedure. Too short interval takes too much computing time. Thus, adopting appropriate wear step is necessary to improve the computational efficiency. As for spherical plain bearing, wear depth of the central region increased quickly at the beginning because of the higher contact pressure. With wear distance went on, the contact pressure on the border region of the contact surface increased and that of the middle region decreased. At last, oscillating wear of the bearing achieved a steady state, called linear wear state. In order to simulate the rapid wear depth change at the beginning, a varying wear step was employed for the wear process. As shown in Table 1, in the early steps, a smaller wear step was implemented while a greater one was used in the subsequent steps. Thus, 176 times iteration calculations would be implement for the wear simulation of 25000 oscillation cycles.

4 WEAR SIMULATION RESULTS AND DISCUSSIONS

The spherical plain bearing used in this study was aluminum alloy bearing but lubricated with woven fabric composite liner. The wear occurs on the contacting surfaces between inner ring and outer ring. In the swing process of the bearing, the aluminum alloy mass loss on the outer surface of the inner ring is very small compared with one of woven fabric liner pasted on the inner surface of the outer ring. That is why the wear takes place mainly on fabric liner of the inner surface of the outer ring. So, only the mass loss of the self-lubricating liner is considered in wear simulation, while ignoring the material loss of aluminum alloy. Some parameters were set in the wear simulation program. The sphere diameter of the inner ring (d_k) was 126 mm, the applied load was 158 kN, the frequency of oscillation was 0.2 Hz, the oscillation angle was +25°~-25°, the average wear rate was 9.76×10^{-7} $mm^3/(Nm)$ [11], and the room temperature was 25°C. Material properties of the spherical plain bearing are given in Table 2.

Table 2. Material properties of Spherical plain bearing

Elastic Constant	Outer Ring	Inner Ring	fabric liner
E_1/GPa	73.1	73.1	52.04
E_2/GPa			4.71
ν_{12}	0.33	0.33	0.37
G_{12}/GPa			1.84
G_{23}/GPa			3.45

Through wear simulation of 25000 oscillating cycles for the spherical plain bearing with self-lubricating, Fig. 6 shows the morphology on inner face of outer ring. Then, wear depth of the inner face of outer ring could be obtained, as shown in Figure 7. It is found that wear is larger in the middle region and is decreased from the middle region to the two border regions. In addition, wear at both end points is greater than that of the adjacent nodes. The maximum wear depth is 0.0731mm and occurs at the central contact region. Through comparison with experimental result (Table 3), close agreement between the FEA predictions and experimental result is found for maximum wear depth. Actually, the practical wear rate is not a constant during the oscillating process. However, during the simulation, the average wear rate of the liner is employed. This may account for that the FEA result is slightly larger than the experimental result.

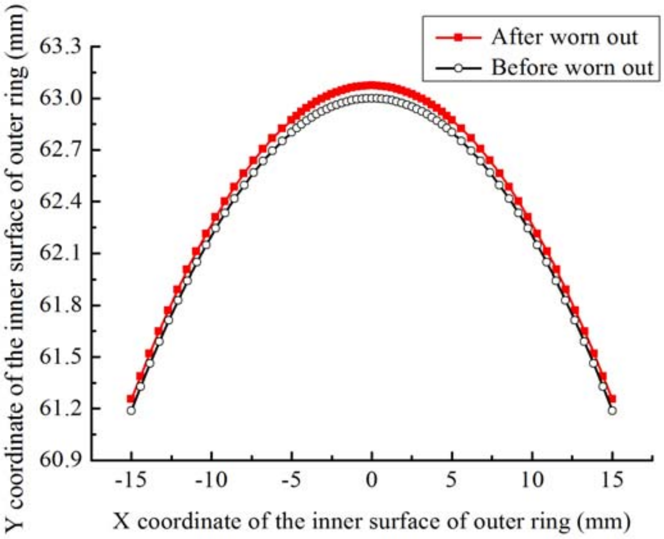

Figure 6. Comparison of the inner surface of outer ring before and after wear.

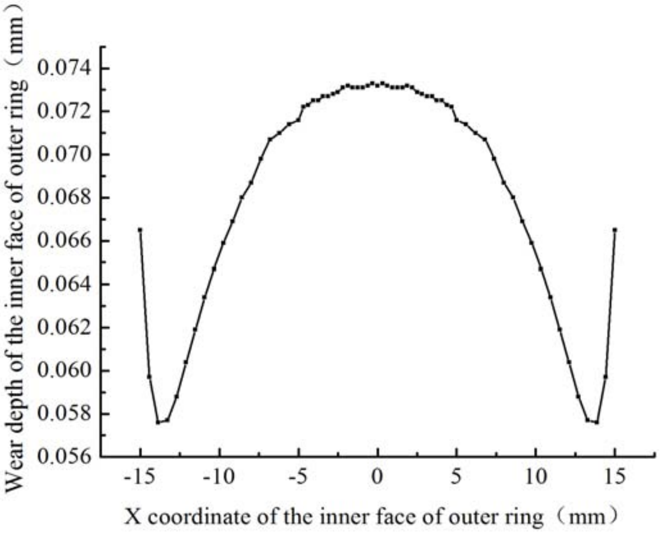

Figure 7. Wear depth of nodes on the inner surface of outer ring.

Table 3. Comparison between simulation and test results of the maximum wear depth

Simulation result (mm)	Test result (mm)	error
0.0731	0.067	9.10%

Since the maximum wear depth occurs on the center node of the inner face of outer ring, the wear simulation program records the relationship between oscillating cycles and wear depth of the node. As shown in Figure 8, the wear depth and oscillating cycles show a linear trend overall. For one thing, the wear rate is constant. For another, changes of the contact pressure during simulation process do little contributions to wear depth. According to this linear trend, it is not difficult to predict that the cumulative wear of the spherical plain bearing with self-lubricating will reach 0.19 mm (as a half of the unit height) after 64945 oscillating cycles, then we need to divide up the grid for the finite element model once more in order to ensure the accuracy of the analysis. Based on the allowable amount of wear, we could predict the life span of the spherical plain bearing with self-lubricating.

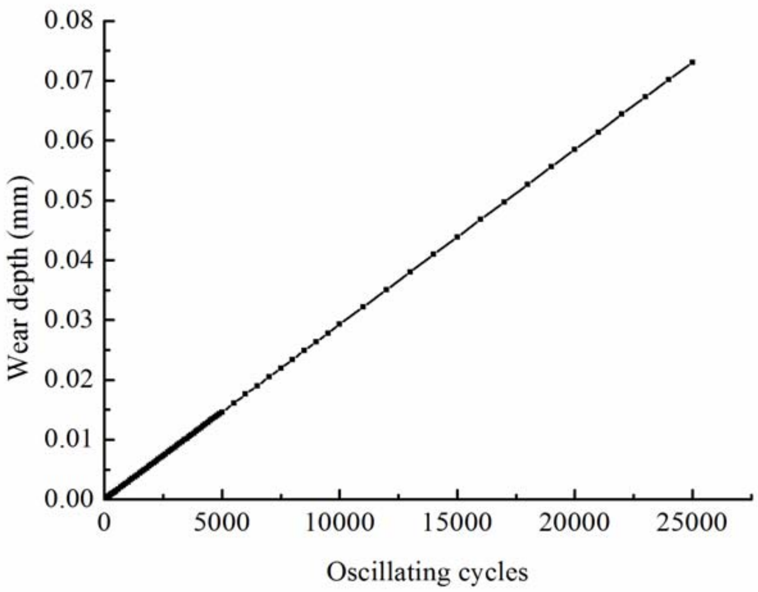

Figure 8. Wear depth changes of the central node on the outer ring with oscillating cycles

5 CONCLUSION

A good way to predict wear life of mechanical components is provided when combining the finite element theory with numerical simulation methods. Through discretizing wear process into wear simulation step, total wear could be calculated using Euler integration scheme. For the given spherical plain bearing example, the numerical and experimental results show close agreement. It is found that the maximum wear depth is 0.0731mm, which occurs on the middle area of the inner surface of outer ring. Compared with wear test results, the relatively error of the maximum wear depth is about 9.10%. The relationship between the wear depth and oscillating cycles on middle area of the inner surface of outer ring is almost linear.

The above analysis results show that the complex nonlinear wear process can be simulated with a series of discrete quasi static models. The 3D thermo-mechanical finite element model and 2D wear simulation program designed could provide practical mechanical and tribological analysis tools to predict wear problems for spherical plain bearings.

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