Numerical Simulation of Sliding Wear for Self-lubricating Spherical Plain Bearings

Xuejin Shen¹,*, Yunfei Liu¹, Lei Cao¹, Xiaoyang Chen¹

¹Department of Mechanical Automation, Shanghai University, Shanghai 200072, China.

Manuscript received February 10, 2012; in revised form April 18, 2012

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 liners. 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 and this is in close agreement with test results. The relative error of the maximum wear depth between the FEA prediction and experimental results is a little more 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.

KEY WORDS: Spherical plain bearing; Finite element method (FEM); Wear simulation; Thermal analysis

© 2012 Brazilian Metallurgical, Materials and Mining Association. Published by Elsevier Editora Ltda. All rights reserved.

1. Introduction

The diversity and complexity of wear phenomenon make it difficult to accurately predict wear life of mechanical parts. The most confident knowledge about the friction pair tribological behaviour can be achieved by making a great number of wear experiments. However, experimental exploration is not only costly, but also not satisfactory when it comes to practical problems of uneven load distributions as well as changeable loads, 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 tribology¹,² and has demonstrated its strong vitality. FEM is widely used to simulate wear progress of mechanical parts. Hegadekatte et al.³⁴ calculated wear of the micro-mechanical devices based on finite element simulations. Experimental results were in good accordance with the simulation results. Kim et al.⁵ simulated a block-on-ring experiment and achieved good results. FEM was also 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 alloy⁶.

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 etc. Fig. 1 gives the structure schematic diagram of these type bearings. 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
Numerical Simulation of Sliding Wear for Self-lubricating Spherical Plain Bearings

3. Finite Element Modeling and Simulation

3.1. Finite Element Modeling

The spherical plain bearing shown in Fig. 1 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 composed of woven fabric liner. For simulating the experimental conditions of the bearing system (Fig. 2), a test ring and shaft were also implemented in the modeling, both of which were of 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. Shen et al. [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 (Fig. 3). Therefore, the maximum wear depth would occur in the same section in terms of Archard’s wear model. In order to simplify calculations, two dimensional finite element wear simulation model of the spherical plain bearing was established (Fig. 3).

\[
h^w = \int k_D \cdot p \cdot ds
\]  

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:

\[
\frac{V}{s} = k \cdot \frac{F_N}{H}
\]  

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, \( \Delta A \), 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, \( \Delta A \), and for the increment of sliding distance, \( ds \):

\[
\frac{dV}{ds \cdot \Delta A} = k \cdot \frac{F_N}{H \cdot \Delta A}
\]

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:

\[
\frac{dh^w}{ds} = k_D \cdot p
\]

where \( k/H \) is replaced 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

\[
h^w = \int k_D \cdot p \cdot ds
\]

Fig. 1 Schematic of spherical plain bearing with self-lubricating fabric liner on the inner surface of the outer ring. The main failure form of these type bearings is the wear of the woven fabric liner.

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

The flow chart of the finite element wear simulation procedure consists of a series of thermo-mechanical coupled solution steps (Fig. 4). 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. 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 to the wear depth, the FE model was updated. If oscillating cycles, \( n \geq n_{\text{max}} \) (predetermined maximum oscillating cycles) or the node temperature, \( T \), exceeds the maximum allowable temperature, \( T_{\text{up-limit}} \), the cycle of calculation would be stopped, otherwise it would go to the next iteration process until the above two conditions were 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.

In order to simulate wear of the contact surface, the nodes coordinate position 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. Therefore, 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 the finite element model.

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. As 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. Therefore, 176 times iteration calculations would be implement for the wear simulation of 25,000 oscillation cycles.

4. Wear Simulation Results and Discussions

The spherical plain bearing used in this study was aluminum alloy bearing 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 the woven fabric liner pasted on the inner surface of the outer ring. That is why the wear takes place mainly on the fabric liner of the inner surface of the outer ring. So, only the mass loss of the self-lubricating liner is considered in the wear simulation, while ignoring the material loss of

<table>
<thead>
<tr>
<th>Oscillating Cycles, ( n )</th>
<th>Wear Step</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n &lt; 200 )</td>
<td>2 cycles</td>
</tr>
<tr>
<td>( 200 \leq n &lt; 500 )</td>
<td>50 cycles</td>
</tr>
<tr>
<td>( 500 \leq n &lt; 5,000 )</td>
<td>100 cycles</td>
</tr>
<tr>
<td>( 5,000 \leq n &lt; 10,000 )</td>
<td>500 cycles</td>
</tr>
<tr>
<td>( n \geq 10,000 )</td>
<td>1,000 cycles</td>
</tr>
</tbody>
</table>

Table 1  Adaptive wear step

![Fig. 4 Wear simulation flow chart of spherical plain bearing](image-url)
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 $+25^\circ--25^\circ$, the average wear rate was $9.76 \times 10^{-7}$ mm$^3$/Nm$^{[11]}$, and the room temperature was 25°C. Material properties of the spherical plain bearing are given in Table 2.

Through wear simulation of 25,000 oscillating cycles for the spherical plain bearing with self-lubricating, Fig. 5 shows the morphology on the inner face of the outer ring. Wear depth of the inner face of outer ring could be obtained (Fig. 6). It is found that wear is larger in the middle region and decreases 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 0.0731 mm and occurs at the central contact region. Compared with wear test results of 0.067 mm, the relatively error of the maximum wear depth is about 9.10%. The FEA prediction coincides well with the experimental result 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 the FEA result be slightly larger than the experimental result.

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 Fig. 7, the wear depth and oscillating cycles show a linear trend overall. For one thing, the wear rate is constant, for another, changes in the contact pressure during simulation process have 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 (half of the unit height) after 64,945 oscillating cycles, then the grid for the finite element model needs to be divided once more in order to ensure the accuracy of the analysis. Based on the allowable amount of wear, the life span of the spherical plain bearing with self-lubricating could be predicted.

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 steps, total wear could be calculated using Euler integration scheme. For the given spherical plain bearing example, the numerical and experimental

<table>
<thead>
<tr>
<th>Elastic Constant</th>
<th>Outer Ring</th>
<th>Inner Ring</th>
<th>Fabric Liner</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_1$/GPa</td>
<td>73.1</td>
<td>73.1</td>
<td>52.04</td>
</tr>
<tr>
<td>$E_2$/GPa</td>
<td>4.71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$v_{12}$</td>
<td>0.33</td>
<td>0.33</td>
<td>0.37</td>
</tr>
<tr>
<td>$G_{12}$/GPa</td>
<td></td>
<td></td>
<td>1.84</td>
</tr>
<tr>
<td>$G_{23}$/GPa</td>
<td></td>
<td></td>
<td>3.45</td>
</tr>
</tbody>
</table>

Fig. 6  Wear depth of nodes on the inner surface of outer ring

Fig. 7  Wear depth changes of the central node on the outer ring with oscillating cycles

Table 2 Material properties of spherical plain bearing
results show close agreement. It is found that the maximum wear depth of 0.0731 mm occurred in the middle area of the inner surface of outer ring. The relatively error of the maximum wear depth is about 9.10%. The relationship between the wear depth and oscillating cycles in 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.

Acknowledgements

This work is supported by the Costind of China (JPPT-115-3-1338), High and New Engineering Program of Shanghai (No. D.51-0109-09-001) and Innovative Team Program of Universities in Shanghai (B.48-0109-09-002).

REFERENCES