Research and Application of Virtual Simulation Technology in the Aerospace Bearing Design and Manufacture

Liu Jiangshan[1] and Chen Ming[2]

[1] *Tongji University, School of Mechanical Engineering, 201804 Shanghai, China*
[2] *Tongji University, Sino-German College of Applied Sciences, 201804 Shanghai, China*

Abstract. Bearings are widely used in aerospace and other fields, its performance directly affects the production efficiency and safety. Nowadays, virtual simulation technology has become an indispensable part of intelligent manufacturing field. As a virtual simulation technology, FEA has been widely used in bearing design. China needs to import many aerospace bearings every year in aerospace area, Chinese national defense and other high precision technology is limited because the blockade of advanced bearing technology. We can use dynamics modeling and virtual simulation technology to achieve the predictive design, and strive to achieve foreign level. In this paper, the author proposed a method of bearing design based on virtual simulation technology. The factors of bearing which affect the dynamic characteristics are considered, the process of design bearing based on virtual simulation is also considered. According to the different design parameters, the simulation results are used to verify the rationality, these can reduce the cost and improve the reliability. The virtual simulation technology is applied to design the 7016C angular contact ball bearing which used in aerospace area, and supported decision-making in structure design and data analyze. Finally, The feasibility of this method is verified by experiments..

1 Introduction

With the development of computer technology and digital technology, product design engineers in the field of intelligent manufacturing can use virtual simulation technology and product design synchronization to carry out the design of human-computer interaction [1], and use the obtained simulation results to guide the design of the product. As an import technology of virtual simulation, CAE (Computer Aided Engineering) technology is a rapid development of computing technology, it is a core technology to achieve major engineering and industrial product design analysis, simulation and optimization. At present, the global industrial revolution, the manufacturing transformation and upgrading accelerate the CAE technology exploration and dependence, more and more enterprises take the simulation as an important part of manufacturing innovation [2]. The FEA (finite element analysis) process contains a large amount of initial information that needs to be processed, and also generates a certain amount of analysis result information, which facilitates the understanding and application to the analyst, and let them to observe the simulation results quickly and accurately [3]。

Rolling bearings are one of the most widely used parts in aerospace area and other modern productions. They are widely used in various rotating parts of aerospace products [4-5]. They have advantages of little starting torque, little friction and easy replacement. we need to learn from foreign technology and achieve our own design bearings. As we all know, it is difficult to accurately grasp the bearing design parameters in the design processes. The dynamic performance is very complex in the rotation processes between the parts of bearing, so it involves many disciplines and technical fields [6].

Bearing virtual simulation technology is a combination of mathematics, computer and signal processing combined disciplines [7]. Through the virtual simulation technology, you can get the dynamic parameters in the process of bearing rotation,and also can evaluate the performance of the bearing, so as to provide a reference for the design and optimization bearing. Bearing virtual simulation technology began in the late 1950s, Jones A B first applied the computer technology to analyze ball movement and friction characteristics of the ball bearing and proposed quasi-static analysis method of the rolling bearing [8]. With the development of bearing theory and computer technology, the simulation technology is really used in the rolling bearing analysis field after the middle 1970s [9]. In the process of virtual design, it emphasizes designing, analyzing, debugging and manufacturing, the digital virtual simulation in the virtual environment formed by the computer before the product is put into operation and completing the problem in the process of designing.

2 Analyze the structure and select the design parameters

The 7016C angular contact ball bearings contain four parts: outer ring, inner ring, roller and cage. It is widely used in aerospace area and the structure diagram is shown in Fig. 1.

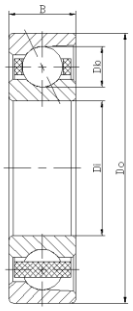

Figure. 1. The structure model of 7016C bearing

In order to verify the rationality of bearing design, 7016C (self-designed) means bearing designed by self, 7016C (FAG) means bearing imported from FAG company. The main structural parameters of the two kinds of bearings are shown in Table 1.

Table 1. The main structure parameters of designing

Name	*7016C（self-designed）*	*7016C（FAG）*
outer diameter	125mm	125mm
Inner diameter	80mm	80mm
width	22mm	22mm
roller diameter	13.494mm	14.288mm
Number of roller	20	19

3 Establish vibration equation and mathematical model of bearing

In order to study the dynamic characteristics of the bearing, Gupta considered the influence of the ball mass and the displacement of the Hertz load in the research process, a six degree of freedom model is used to simulate the steel ball movement process [10]. Walter analyzed the motion model of ball bearing under the action of lubricating oil [11].

The vibration of the ball bearing is mainly caused by non-linear force in the rotation process, mainly including three categories:

(i) The inherent vibration of bearing structure.

$$\begin{cases} f_x = \dfrac{\sqrt{K_x/M}}{2\pi} \\ f_y = \dfrac{\sqrt{K_y/M}}{2\pi} \end{cases} \quad (1)$$

The natural vibration frequency of the bearing can be calculated by:

Where M is the mass of the bearing system.

(ii) The vibration caused by unbalance force.

The expression of the vibration frequency produced by the unbalanced force is as follows and its value is equal to the frequency of shaft rotation:

$$f = \frac{\omega}{2\pi} \quad (2)$$

(iii) The vibration caused by the rolling element through the bearing area

When the outer ring fixed, the inner ring rotated, the bottom roller rolled from the load area to the non-load area, it will cause variable stiffness vibration.

When the number of compression rollers pass through the bearing area is odd and there is a roller on the load line, it is called "odd pressure" state. When the number of compression rollers is even and symmetrical on both sides of the load line, it is called "even pressure". The pressure distribution is non-linear and its expression is as follows:

$$f_{vc} = \frac{\omega_{vc}}{2\pi} = \frac{\omega_b N_b}{2\pi} \quad (3)$$

In order to simulate the bearing rotation process, this paper bound the axial direction (Z-axis direction), loaded the radial direction (Y-axis direction) when analyzed, the working system model is shown in Fig. 2.

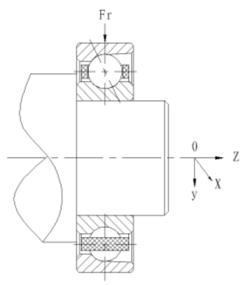

Figure. 2. The working system model of 7016C bearing

The vibration equation is established according to Fig. 2 showed as follows:

$$\begin{cases} M\ddot{x} + C\dot{x} + K_n \sum_{j=1}^{N_b} (x\cos\theta_j + y\sin\theta_j - \\ \gamma)^{3/2} \cos\theta_j = F_r + M e_m \omega^2 \cos\omega t \\ M\ddot{y} + C\dot{y} + K_n \sum_{j=1}^{N_b} (x\cos\theta_j + y\sin\theta_j - \\ \gamma)^{3/2} \cos\theta_j = M e_m \omega^2 \sin\omega t \end{cases} \quad (4)$$

In the formula above: M is the quality of bearing system; C is the damping of bearing system, K is the imbalance of the eccentricity of the bearing system. it can be seen from the formula above. The vibration excitation force mainly from the Non-linear bearing force and unbalanced force.

4 Establish the dynamic characteristics and dynamics equation of bearing

In solving the dynamic simulation of rolling bearings, the central difference method is generally used, because this method does not need to balance the iteration and does not need to directly solve the tangent stiffness, so it speeds the solution and it also saves a lot of computing time.

It is assumed that the displacement of any node has two components in direction, it is the displacement component u along the radial direction and the displacement component w in the axial direction and regardless of the influence of the damping factor. At time t = 0, the displacement, velocity and acceleration are known and the time domain n is divided into Δ t. Then the system is solved by the finite element method likes this:

$$M\ddot{a}_t + C\dot{a}_t + Ka_t = Q_t \tag{5}$$

In the formula above: M, C, K and Q_t are the mass matrix, damping matrix, stiffness matrix and the load vector of the nodes. $\ddot{a}_t$, $\dot{a}_t$ and a_t are the acceleration vector, velocity vector and displacement vector of the system nodes.

The displacement do Taylor expansion at time t and take the highest quadratic polynomial to have its approximation:

$$a_{t+\Delta t} = a_t + \Delta t\,\dot{a}_t + \frac{\Delta t^2}{2}\ddot{a}_t \tag{6}$$

The relationship between the acceleration and the displacement is obtained by solving the above equation:

$$\ddot{a}_t = \frac{1}{\Delta t}(\dot{a}_{t+\Delta t} - \dot{a}_t) = \frac{1}{\Delta t^2}(a_{t+\Delta t} - 2a_t + a_{t-\Delta t}) \tag{7}$$

The relationship between speed and displacement is expressed as:

$$\dot{a}_t = \frac{1}{2\Delta t}(a_{t+\Delta t} - a_{t-\Delta t}) \tag{8}$$

Put the above two formulas into the formula (5) you get the following formula:

$$Q_t - (K - \frac{2}{\Delta t^2}M)a_t - (\frac{1}{\Delta t^2}M - \frac{1}{2\Delta t}c)a_{t-\Delta t} = (\frac{1}{\Delta t^2}M + \frac{1}{2\Delta t}c)a_{t+\Delta t} \tag{9}$$

The equation above is the classical formula of the central difference method, it can be seen from above, if we know $a_{t-\Delta t}$ and a_t , so $a_{t+\Delta t}$ can be solved, and then can be solved the speed and acceleration at time t.

5 Establish the 3-D model and finite element model of bearing

5.1 Establish the 3-D model of bearing

Using Pro/E to establish the 3-D model of 7016C angular contact ball bearing, as is shown in Fig. 3. Consider the complexity of the actual bearing model and the limitations of simulation, the chamfer and oil film and other factors have little influence to the dynamic characteristics, deal with the model as following:

(ⅰ) Ignore the chamfer of the bearing.

(ⅱ) Ignore the radial and axial clearance of bearing.

(ⅲ) Ignoring the effect of lubricating oil to bearing vibration.

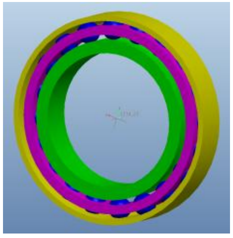

Figure. 3. The 3-D model of 7016C bearing

5.2 Establish the finite element model of bearing

Considering that the strain of the roller is the largest, the deformation of the inner and outer ring is small, the deformation of the cage can be neglected. Therefore, when select the material model, the cage is defined as rigid body, the roller, inner ring and outer ring are defined as elastoplastic. It will greatly reduce the computational time after defined as rigid body because the freedom degrees of all nodes in the rigid body are coupled to the mass center. No matter how many nodes are defined by the finite element model, the rigid body has only six freedom degrees, The motion is calculated from the centroid and passes the corresponding displacement value to the node.

Transform the 3-D model established by Pro/E into IGES format and import into finite element software. Select shell 163 unit and solid 164 unit. The material of inner and outer ring is GCr15 steel, the cage is phenolic laminated cloth, the density is ρ = 7800×10^{-6}kg/mm^3, the elastic modulus E is 208 GPa, the Poisson's ratio μ is 0.3 [12]. The mesh is divided by scanning and mapping. Establish a contact between the inner and outer ring and the cage. The contact type is automatic face-to-face contact and the static friction coefficient is 0.35, 0.35 and 0.2, the dynamic friction coefficient is 0.16, 0.16 and 0.1. The rigid surface of the outer ring is set to full constraint. The working bearing receives the pressure and speed. The pressure is reduced to uniform force applied to the lower half surfer of the inner ring and the speed applied to the rigid surface of inner ring.

The simulation model of bearing is shown in Fig. 4.

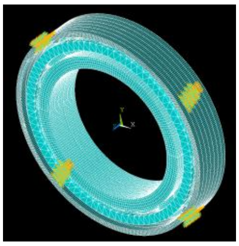

Figure. 4. The simulation model of 7016C bearing

6 Contrast analysis and simulation of the vibration characteristics of bearing

6.1 Analysis of the simulation results of bearing vibration of 7016C (self-designed)

Under the load of 10 KN and the speed of 1800 r/min, the analysis results of 7016C (self-designed) bearing is shown in Fig. 5 to Fig. 7. Three moments of the calculation results are analyzed (0.02 s, 0.05 s, 0.08 s) .

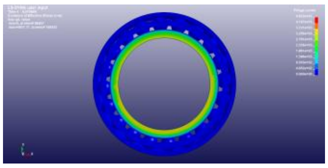

Figure.5. The equivalent stress plot of vibration bearing in 0.02 seconds

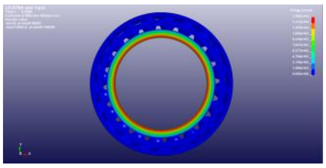

Figure.6. The equivalent stress plot of vibration bearing in 0.05 seconds

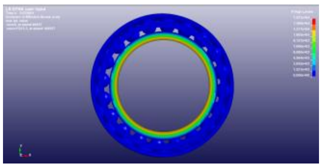

Figure.7. The equivalent stress plot of vibration bearing in 0.08 seconds

It can be seen from the above Fig.5 to Fig.7, the larger stress of 7016C (self-designed) bearing generally appear in the contact area of roller and the inner and outer ring. The maximum stress value and the location of the maximum stress will be changed with the bearing rotation. As the time increases, the stress on the bearing is gradually reduced, because the bearing will start to receive a greater impact. The stress value tends to be stable until the steady operation, the stress value slowly becomes smaller when the bearings gradually stop running.

It can be seen from Fig.8, when the 7016C (self-designed) bearing begins to rotate, it produces a strong vibration because the roller receives a sudden load. With the stable operation of the bearing, the vibration value tends to be stable. The maximum stress value exhibits a certain periodicity, which is related to the periodic entry of the bearing element into the load bearing area and the non-load area.

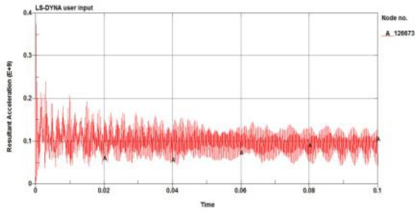

Figure.8. The vibration distribution of bearing over time

6.2 Analysis the simulation results of bearing vibration of 7016C (FAG)

Under the load of 30 KN and the speed of 3000 r/min, the analysis results of 7016C (FAG) bearing is shown in Fig. 9 to Fig. 11. Three moments of the calculation results are analyzed (0.02 s, 0.05 s, 0.08 s) .

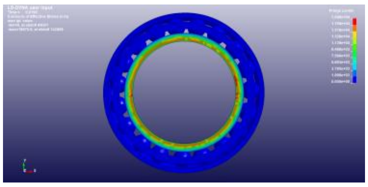

Figure.9. The equivalent stress plot of vibration bearing in 0.02 seconds

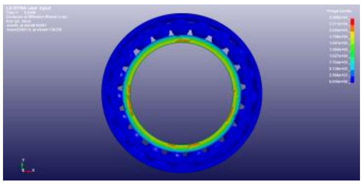

Figure.10. The equivalent stress plot of vibration bearing in 0.05 seconds

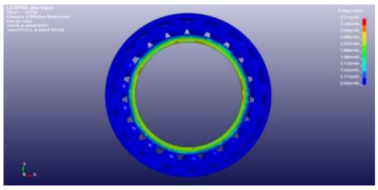

Figure.11. The equivalent stress plot of vibration bearing in 0.08 seconds

It can be seen from the above Fig.9 to Fig.11, the stress is small when the 7016C (FAG) bearing begins to rotate. The stress gradually becomes larger with the rotation process. The maximum stress appears below a certain area in the contact surface of roller and the inner and outer ring , The value gradually decreases from the inside to the outside, the stress is mainly distributed in the bearing area. The stress value in the bearing area is significantly greater than the stress value in the non-bearing area. The area where the stress occurs is elliptical.

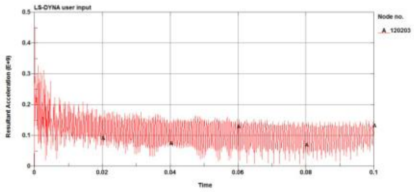

Figure.12. The vibration distribution of bearing over time

It can be seen from Fig.12, when the 7016C (FAG) bearing begins to rotate, it produces a strong vibration because of the roller received a sudden load, with the stable operation of the bearing, the vibration value tends to be stable.

6.3 Contrast analysis the simulation results of bearing vibration between 7016C (self-designed) and 7016C (FAG)

In order to verify the rationality of self-designed bearing, applied the load of 30 KN and the speed of 8000 r/min on the 7016C (self-designed) bearing and 7016C (FAG) bearing. After dynamic simulation, three moments of the calculation results are analyzed (0.02 s, 0.05 s, 0.08 s). The results are shown in Fig. 13 to Fig. 18.

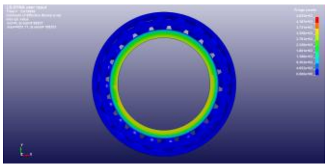

Figure.13. The equivalent stress plot of vibration（self-designed） bearing in 0.02 seconds

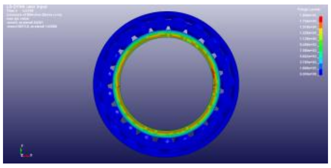

Figure.14. The equivalent stress plot of vibration（FAG） bearing in 0.02 seconds

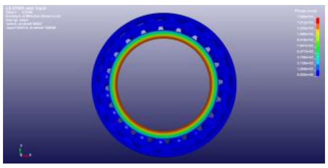

Figure.15. The equivalent stress plot of vibration（self-designed）bearing in 0.05 seconds

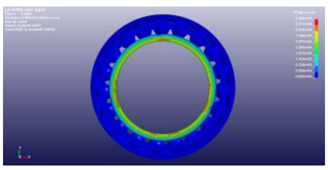

Figure.16. The equivalent stress plot of vibration（FAG) bearing in 0.05 seconds

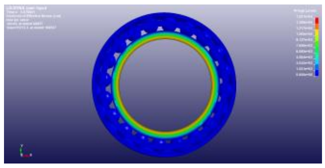

Figure.17. The equivalent stress plot of vibration（self-designed）bearing in 0.08 seconds

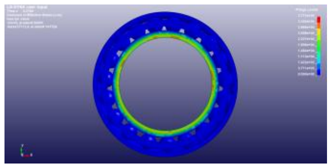

Figure.18. The equivalent stress plot of vibration（FAG) bearing in 0.08 seconds

It can be seen from Fig. 13 to Fig. 18, the stress of the 7016C (self-designed) bearing is bigger in the beginning, but as the operation progresses, the stress becomes smaller and tends to be smooth. The stress of the 7016C (FAG) bearing is smaller in the beginning, but the stress increases with the rotation process. The stress value is three times higher than 7016C (self-designed) bearings.

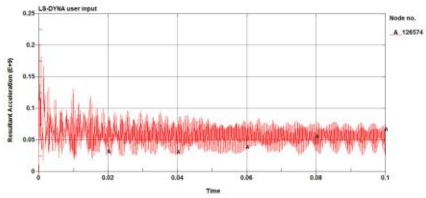

Figure.19. 30 KN,8000 r/min,the vibration distribution of 7016C （self-designed）bearing over time

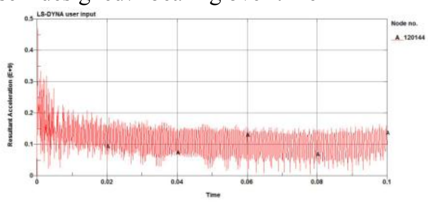

Figure.20. 30 KN,8000 r/min,the vibration distribution of 7016C (FAG) bearing over time

It can be seen from Fig. 19 to Fig. 20, when the bearing starts to rotate, the vibration is increased due to the effect of a sudden applied load. As the bearing is stable, the vibration value tends to be stable, and the vibration value of 7016C (FAG) bearing is greater than the vibration value of 7016C (self-designed) bearing .

7 Experiment analysis

In order to verify the feasibility of the method in designing bearings, select the GCr15 steel material, the process into bearing after a certain heat treatment process and the processing parameters shown in Table 2.

Table.2. The table of processing parameters

Name	Processing parameters
Datum flatness（um）	0. 42
Cutting speed V（m/min）	130
Feed speed f（mm/r）	0.03
Cutting amount a_p (mm)	0.025

The performance evaluation indicators of the bearings are mainly include surface roughness, channel roundness, hardness, surface burns, residual stress and etc on. The results are shown in Table 3. All the indicators meet the requirements.

Table.3. The results of experimental

Name	Test value
Roughness（um）	< 0.1
Roundness（um）	0.8
hardness（HV）	774.5
Burn degree	Nothing
Residual stress situation	All are compressive stress, controllable

8 Conclusions

The paper is based on the computer virtual simulation technology and uses the 7016C angular contact ball bearing as the research object. Firstly, the 3-D model is established by using Pro/E. Secondly, introduce the 3-D model into the finite element software ANSYS to obtain the finite element model. Finally, uses the simulation analysis software LS-DYNA to analyze the dynamic simulation of 7016C (self-designed) bearing and 7016C (FAG) bearing, get the stress and dynamic characteristics of the two kinds of bearing which changed with the pressure and the speed. Prove the structural parameters are reasonable through the experiment of 7016C (self-designed) bearing, it shows that the method is feasible. The method can provide the basis theoretical and analysis foundation for the virtual simulation design and fault diagnosis of the bearings.

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