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A finite-element analysis of the connecting bolts of slewing bearings based on the orthogonal method †

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Abstract

This paper presents an analysis of the main factors affecting the performance of connecting bolts for slewing bearings. For double row four-point contact ball bearings, major factors include the preload, friction coefficient and height of the bushes. First, bolt connection performances with different levels of each factor are calculated with the finite element method (FEM). Then, the calculation results are analyzed with the orthogonal method. The analysis indicates that the preload is the most important factor affecting the bolt connection performance, followed, to a lesser degree, by the height of the bushes. The friction coefficient is the least important factor.

Keywords: Bolt connection; Slewing bearing; FEM; Orthogonal method

1. Introduction

Bolt connection performance is important to the overall performance of slewing bearings in operation, as most slewing bearings rely on the connecting bolt to transfer the loads to the support piece. Bolt failure can be attributed to such factors as fatigue cracks caused by fatigue failure and loosening caused by the alternate stress when slewing bearings are working. Also, in some cases the connecting bolt may snap. Previous studies show that major factors affecting bolt connection performance include the preload, the friction coefficient of the contact surface between the bolt and connecting part, the height of the bushes [1], the bearing rings' rigidity [2], the height of the installation seat, the bolt stiffness, the method of installation of the bolts [3], etc. Some scholars have analyzed bolt connection performance under different preloads, and their studies show that as preload increases, alternate stress of the bolt will be reduced [4]. Other scholars, through establishing special models, have studied the effect of bolt stiffness on connection performance with the finite element method (FEM) [5]. In addition, some researchers have established ways of bolt connection, and verified their reliability through analysis [6]. However, the interaction among these factors can have an impact on the overall performance of the connecting bolt, which should not be ignored. In this paper, we will apply the orthogonal design method to identify to what extent the various factors affect bolt connection performance. The main loads applied to slewing bearings are axial force and overturning moment, as shown in Fig. 1. Therefore, the radial force will not be considered in this paper. Data needed for the orthogonal design will be obtained with FEM.

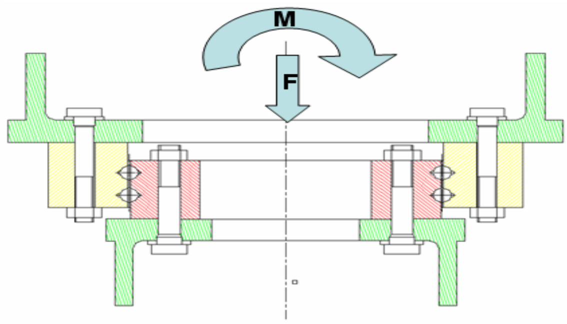

Fig. 1. Bolt connection in slewing bearings.

2. Method of orthogonal design

Orthogonal design is an experimental method used to analyze various factors by means of the orthogonal table [7]. It is an efficient, fast and economical experimental design method. Commonly used orthogonal design methods include variance analysis and intuitive analysis. Orthogonal design can be divided into single index design and multi-index design according to the index number of the test. There are two indicators

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Table 1. Orthogonal design factors and levels.

Factor code	Factors	Levels				
		1	2	3	4	5
A	Preload (MPa)	40%σ_s	50%σ_s	60%σ_s	70%σ_s	80%σ_s
B	Friction coefficient	0.15	0.2	0.25	0.3	0.35
C	Blank column	-	-	-	-	-
D	Height of bushes (mm)	5	10	15	20	25

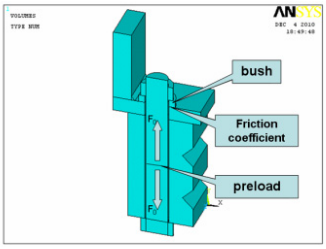


Fig. 2. Single bolt connection in the slewing bearing.

for the factors analyzed in this paper: namely, the alternate stress and the maximum tensile stress, both when the connecting bolt is under load. In this paper, we will make a contrastive analysis of the computation results of FEM with the multi-index variance analysis method and intuitive analysis method.

3. Orthogonal design for the factors

There are many factors affecting the bolt connection performance of slewing bearings. This paper will consider three major factors including preload, friction coefficient of the contact surface between the bolt and connecting part, and the height of the bushes. The bolt stress caused by combinations of different levels of the factors is computed with FEM. In view of the complexities involved in overall bolt connection performance, this paper will focus on single bolt connection performance since analyzing bolt connection performance by considering only the stress limit is common practice and produces highly reliable results. The model of a single connecting bolt is shown in Fig. 2.

3.1 Orthogonal design for connection bolts

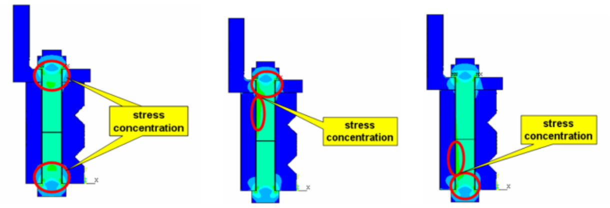
As mentioned above, three main factors for the bolt connection performance of slewing bearings will be analyzed with the orthogonal design method. According to this method, three factors are considered as independent variables, and the effect on the bolt connection performance is studied. There are three factors for the orthogonal design, and each factor is divided into five levels, as shown in Table 1. σ_s is the yield limit stress value of the bolt material. It needs to be computed 125 times with the full factors orthogonal design method, which will

Table 2. Orthogonal design table.

Test number	A	B	C	D	Test number	A	B	C	D
1	1	1	1	1	14	4	1	3	5
2	2	2	2	2	15	5	2	4	1
3	3	3	3	3	16	1	4	2	5
4	4	4	4	4	17	2	5	3	1
5	5	5	5	5	18	3	1	4	2
6	1	2	3	4	19	4	2	5	3
7	2	3	4	5	20	5	3	1	4
8	3	4	5	1	21	1	5	4	3
9	4	5	1	2	22	2	1	5	4
10	5	1	2	3	23	3	2	1	5
11	1	3	5	2	24	4	3	2	1
12	2	4	1	3	25	5	4	3	2
13	3	5	2	4					

result in the establishment of 125 models for the bolt connection. Inevitably, such a long cycle of computation involves a waste of human resources. Therefore, this paper will adopt the partial factors orthogonal design method. The orthogonal table according to different levels of factors which involves only 25 times of computation is shown in Table 2. The orthogonal table is created according to the orthogonal matrix. From the table, there are four factors and five sectors, which correspond with the experimental purpose and methods. After this, finite element models of the bolt connection with different combinations of different levels of factors shown in Table 2 are established. Then, finite element computations are made with the same boundary conditions. Finally, the maximum stress and alternate stress value are summarized according to the results of computation.

The single bolt connection performance with combinations of different levels of factors are analyzed through the finite element software ANSYS. The finite element model of the connecting bolt is meshed with the SOLID45 element. Furthermore, contact elements are needed between the contact pairs, which are the CONTA174 and TARGE170. There are a total of 182623 nodes and 169188 elements. The connecting bolt is affected by the interaction between loads caused by compression and tension due to slewing bearings supporting overturning moment. Therefore, the stress of the bolt in each combination of factors is computed under three kinds of loads, respectively. The loads include tension, compression, and preload. Comparing the stress values of the bolt under the three kinds of the loads, the maximum stress value with each combination of factors can be identified, and this value is an indicator for the bolt connection performance. Alternate stress is also an important indicator. The bolt stress cloud charts under the three kinds of loads are shown in Fig. 3. From these figures, we can see the change in stress distribution when the bolt is supporting the tension and compression. It follows that the bolt is exposed to different alternate stress when slew bear-



(a) Preload (b) Tension (c) Compression

Fig. 3. Stress cloud charts of the bolts with different loads.

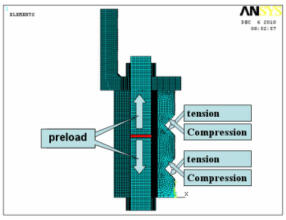


Fig. 4. Finite element model of bolt connection.

ings are rotating. Therefore, besides the computation of the bolt maximum stress, the alternate stress applied to the bolt when slewing bearings are working should be considered as an indicator.

The maximum stress value is the primary indicator to be considered, and the alternate stress is the secondary indicator. The alternate stress is the cyclic stress caused by alternate loads applied to the mechanical components or by the bolt's own rotation [8]. The loads acting on slewing bearings are changing in the process of working, leading to change in the stress to the connecting bolt and thereby causing the alternate stress. In order to analyze the alternate stress quantitatively, amplitude is chosen as an indicator in this paper. The amplitude refers to the difference between the maximum stress under the maximum working load and the maximum stress under the minimum load.

3.2 Results of orthogonal design

The orthogonal design of the bolt is based on ANSYS. In order to increase the efficiency, a symmetrical treatment is adopted to establish the finite element model. In other words, only half of the model is computed and the symmetry constraints are applied in the symmetric plane. The loading surfaces are the contact surface of the bearing rings with bolt connecting and rolling bodies. The specific load conditions are shown in Fig. 4. According to the actual loading condition, the working load of the single bolt can be obtained by the formula below [9]:

$$F_A = \frac{1}{COS\beta}\left(\frac{2M_T}{\pi \cdot \mathrm{R}} \cdot \sin\frac{\pi}{z} + \frac{F_{ax}}{z}\right) \quad (1)$$

where β refers to the included angle between the working load direction and the axial direction, z to the number of the bolts that connect the outer ring of the bearing, and R to the radius of the node in the rolling body.

Table 3. Results of variance analysis with orthogonal design.

Factors	SS	df	MS	F	Significance
A	1313533.38	4	328383.35	9183.30	***
B	572.38	4	143.09	4.01	*
C	272.76	4	68.19	1.91	-
D	14763.54	4	3690.89	103.22	**
Error	286.07	8	35.76	-	-
Summation	1329428.13	24	-	-	-

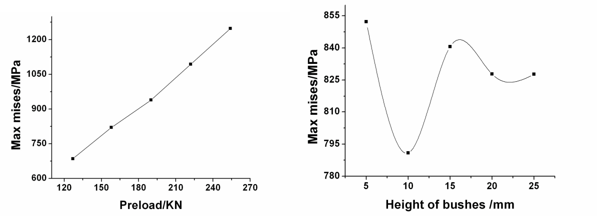
First, the finite element method is adopted to compute the stress of the bolt with different combinations of factors at different levels. Then, the data obtained from computation are handled with intuitive analysis and variance analysis method. Intuitive analysis method can indicate which kind of factor combination is the best, but cannot decide which factor is significant. In order to obtain both the optimal combination and the significant factor, both methods are used in this paper. In view of the large amount of data, the maximum stress and the alternate stress are chosen as indicators in the intuitive analysis and only the maximum stress is chosen as an indicator in the variance analysis. The results are shown in Table 3 and Table 4. In Table 3, SS stands for the sum of squares of deviations which reflects the result differences of different calculations, df for degree of freedom of each factor, MS for the mean squares of deviations which is in order to eliminate the influence related to the number of each factor. Finally. F is used for reflecting the influence degree of different factors. In Table 4, K1 stands for the sum of maximum stress for the first level of every factor, k1 being the mean number. The rest can be done in the same manner.

It can be seen from the table above that when maximum stress is considered the indicator, the preload is identified as the most important factor affecting bolt connection performance followed by the height of the bushes, and the effect of friction coefficient is not prominent. If alternate stress is considered the index, the height of the bushes is identified as the most important factor followed by friction coefficient, and preload becomes the least important. When slewing bearings are working, the maximum stress of the bolt must be below the allowable stress value, and the alternate stress should be minimal. Whichever indicator is considered, it can be seen that the height of the bushes has a more significant effect than friction coefficient. However, the effect of preload shows considerable difference with the two indicators. When maximum stress is considered an indicator, preload will increase as the bolt tensile stress increases. When alternate stress is considered an indicator, the effect of preload is not important. So the bolt performance is computed and analyzed with different preloads and different heights of the bushes.

First, with maximum stress considered as an indicator, the bolt tensile stress is computed under different preloads and

Table 4. Results of intuitive analysis with orthogonal design.

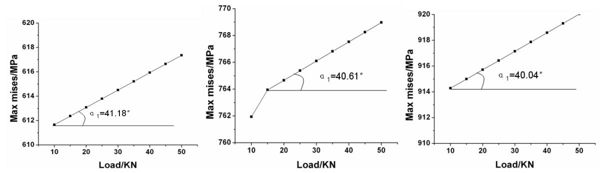
Index		Preload	Friction coefficient	Blank column	Height of the bushes
	K1	3311.69	4948.36	4914.23	5075.67
	K2	4125.11	4961.01	4953.4	4716.02
	K3	4934.14	4950.04	4915.16	5012.91
	K4	5745.40	4908.22	4938.18	4931.76
	K5	6553.60	4902.31	4948.97	4933.58
	k1	662.33	989.67	982.846	1015.13
Max stress (MPa)	k2	825.02	992.20	990.68	943.20
	k3	986.82	990.00	983.032	1002.58
	k4	1149.08	981.64	987.636	986.35
	k5	1310.72	980.46	989.794	986.71
	Range	3241.91	58.70	39.17	359.65
	Primary and secondary order	ADBC			
	Optimal design	$A_1D_2B_5C_1$			
	K1	33.32	34.19	34.22	39.05
	K2	35.65	36.47	35.96	36.29
	K3	34.07	33.93	33.83	34.52
	K4	34.60	33.75	34.47	31.29
	K5	34.80	34.10	33.96	31.29
	k1	6.66	6.83	6.844	7.81
Alternate stress (MPa)	k2	7.13	7.29	7.192	7.25
	k3	6.81	6.78	6.766	6.90
	k4	6.92	6.75	6.894	6.25
	k5	6.96	6.82	6.792	6.25
	Range	2.33	2.72	2.13	7.76
	Primary and secondary order	DBAC			
	Optimal design	$D_5B_4A_1C_3$			



(a) (b)

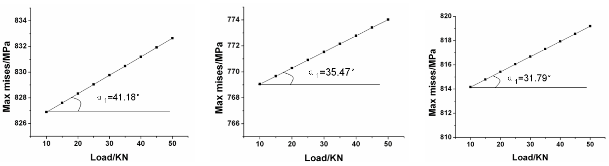
Fig. 5. Maximum stress of the bolt with the same loads and different factors: (a) Preload; (b) Height of bushes.

different heights of the bushes in order to identify the optimal design. The maximum tensile stresses of the bolt under the two conditions above are shown in Fig. 5. As indicated in Fig. 5(a), maximum stress increases significantly when preload increases. Therefore, preload can be identified as the primary factor affecting bolt connection performance when maximum stress is regarded as the indicator. When preload is $60\%\sigma_s$, the



(a) (b) (c)

Fig. 6. Maximum stress variation tendency of the bolts with different preloads: (a) preload=$40\%\sigma_s$; (b) preload=$50\%\sigma_s$; (c) preload=$60\%\sigma_s$.



(a) (b) (c)

Fig. 7. Maximum stress variation tendency of the bolts with different height of bushes: (a) Height =5 mm; (b) Height =10 mm; (c) Height =15 mm.

bolt maximum stress is above the allowable stress value. Consequently, preload should be $40\%\sigma_s$ or $50\%\sigma_s$. Fig. 5(b) shows that when the height of the bushes is 10mm, maximum stress is small, and when the height of the bushes is above or below 10mm, maximum stress is accordingly large.

The connecting bolt often loosens due to alternating loads when working, and in some cases, the bolt may simply drop out. Therefore, it is necessary to make further analysis considering alternate stress as an indicator of bolt connection performance. In order to make an accurate analysis, we will not adopt the method of orthogonal design. Instead, we will compute alternate stress with reference to the change in maximum stress. Figs. 6 and 7 respectively show the variation curve between the maximum tensile stress of the bolt and the values of different preloads and different heights of bushes. Fig. 6 indicates that the variation tendency of the maximum tensile stress of the bolt along with the change in the working loads can be slowed down when preload increases. The slope values become smaller, as can be seen from the curve. From these curves, we can conclude that an increase in the value of preloads will result in a decrease in alternate stress.

Meanwhile, this will also lead to an increase in maximum tensile stress, exceeding the allowable stress value. The optimal preload value can be set at $50\%\sigma_s$ if we consider the results obtained with maximum stress as an indicator. Now the preload can be set at $50\%\sigma_s$, and then, the maximum stress value of bolts with different heights of bushes and different loads will be computed respectively. As shown in Fig. 7, the variation tendency of the bolt maximum stress value with the changing load can be slowed down when the height of the bushes increases, which means that an increase in the height of the bushes will lead to a decrease in the effect of alternating stress on the bolt connection performance. But when combining Fig. 7(b) and (c), we can see that the variation tendency of the bolt maximum stress with changing loads can be stable when the height of the bushes increases. The optimal height of the bushes should be 15mm, if we consider the results of computation with the maximum stress as the indicator. Comparing Fig. 6 with Fig. 7, we can see that the trend in the slope of the curve is consistent with the results obtained with orthogonal design, both showing that the effect of the heights of the bushes on the alternate stress is greater than that of preloads.

4. Conclusions

With the finite element method, this paper has computed the stress distribution of connecting bolts in the double row four-point contact ball bearing under different supporting loads. We have shown that the connecting bolt operates under different alternate loads by comparing the different stress cloud of bolts with the tensile and compressive load.

This paper has analyzed the three major factors affecting bolt connection performance by using the orthogonal design method. It is concluded that the effect of preload and the height of bushes are more significant than that of the friction coefficient of the contact surface between the bolt and the connecting part.

Based on the results of orthogonal design method, a further analysis has been made. It has been discovered that the optimal bolt connection performance can be obtained when preload is 50%σ_s, the height of bushes 15mm, and friction coefficient is 0.35.

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