Optimization of Bearing Displacement in Ship Shafting Alignment Based on Workbench

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Abstract. Shaft alignment plays an important role in the installation of ship propulsion shafting, ensuring the safety and reliability of ship propulsion shafting. The article takes the shaft system of a 3000m ro-ro ship as an example to simplify the model. Use the workbench platform to perform linear alignment, reasonable alignment and bearing displacement optimization on the shaft system. The results are anastomosis with the results of the traditional three-bending moment algorithm. The optimized displacement result of the bearing can be used as a reference data for shafting installation, which has great practical value.

1. Introduction
The ship's propulsion shafting is an important component of the main propulsion power plant. It connects the main engine and the thruster, and is the channel for the main engine's energy conversion and thrust transmission. In order to ensure the long-term safe and normal operation of the shaft system, the shaft system should be designed with sufficient strength and rigidity. In addition, the shaft system should be installed in a reasonable position and condition. Shaft alignment can be considered as the installation process of advancing the shaft system. Many experts and scholars at home and abroad have put forward calculation models and calculation methods suitable for the alignment of various types of ship propulsion shafting [1-2] through research. Through theoretical calculations, a reasonable state of the shaft system is obtained, so that the load on all bearings of the shaft system and the stress in each shaft section are allowed in this state. Within the scope, provide theoretical support and technical support for the installation and safe operation of shafting. At this stage, the bearing displacement is obtained based on experience, which consumes a lot of resources. The article proposes to use finite element tools to solve the reasonable displacement of the bearing, which has instructive significance.

2. Calculation theory and method of shaft alignment
If the shaft alignment is poor, it may cause damage to the bearing, excessive shaft vibration and other hazards. Therefore, the shaft alignment is of great significance in the shaft system design and installation stage. Ship propulsion shaft alignment mainly most commonly used includes Ship shafting alignment methods include static alignment, dynamic alignment and running state alignment.

At present, the shaft alignment is based on Newton's classical mechanics to simplify the shaft system into a simply supported beam model. For the bearing support form, point support or line support can be selected. The calculation accuracy of the two methods is different, and domestic scholars mostly choose point support.
Based on Newton's classical mechanics theory, methods such as three-bending moment method, transfer matrix method, and finite element method are generally used for shaft alignment calculation. The above-mentioned three methods are relatively mature in theoretical research, and their calculation results are in good agreement with the test results, so they are widely used in the field of ship shafting static alignment. For example, Zhou R P [3] and Zhang S P [4] wrote the calculation program for shaft alignment in the VB language environment based on the three-bending moment method and the transfer matrix method; Yang Yong [5] summarized the advantages and disadvantages of the three methods on the basis of studying the theory of shaft alignment, as shown in Table 1.

Table 1 Characteristics comparison of three calculation methods for shafting alignment

| Shaft alignment calculation method | Characteristics                                                                 |
|-----------------------------------|---------------------------------------------------------------------------------|
| Three-moment method               | Simple principle, mature application, complex algorithm, low precision.          |
| Transfer matrix method            | Easy to program, simple algorithm, high calculation accuracy.                    |
| Finite Element Method             | The algorithm is complex, the amount of calculation is large, the precision is high, it is not easy to program, and the computer requirements are high. |

3. Calculation model

The article takes the propulsion shafting of a ro-ro ship as the research object and simplifies the shafting. The main simplification principles are:

i. Use the weight of the propeller shaft, intermediate shaft and gear shaft as a uniform load to act on the beam; The shaft section of the propeller shaft immersed in seawater and lubricating oil should also consider the difference in buoyancy coefficient, and make corrections when calculating the weight of the shaft section. In the article, the requirements for water and oil coating are achieved by modifying the density of the corresponding shaft section.

ii. Propellers, gears, etc. are used as concentrated loads on the shafting during the simplification process. For the propeller, it should be considered that the propeller is fully submerged or semi-submerged by the buoyancy of the water. In the calculation process, the actual weight of the propeller fully immersed in water can be calculated approximately according to the empirical formula.

\[ G_2 = (0.869 \sim 0.87)G_1 \]  

Where, \( G_1 \) - The weight of the propeller in the air, N; \( G_2 \) - The actual weight of the propeller fully immersed in water, N.

The actual weight of the propeller in the semi-immersed state is approximately calculated as:

\[ G_2 = (0.869 \sim 0.87)G_1 \]  

iii. For each bearing fulcrum, a single-point support method is adopted. Since the rear tail bearing is under the cantilever action of the propeller, the supporting point is taken as the distance of one-third of the bearing length from the rear edge of the tail bearing, and the positions of the supporting points of other bearings are taken as the midpoint of the bearing bush length.

According to the above principle of simplification of the shaft system, the shaft system is simplified to obtain the shaft system alignment model data. Save the shaft system calibration model data as a text format file (*.txt), The DM in the workbench module reads the file data, and builds a finite element beam model based on the data. As shown in Figure 1.

Set the material properties according to the working environment of the shaft section. For example, the shaft section is immersed in water, oil and in the air. The buoyancy coefficients are 1025kg/m\(^3\), 850kg/m\(^3\). Therefore, the material density is set to 6825kg/m\(^3\), 7000kg/m\(^3\), 7850kg/m\(^3\). The Poisson's ratio of the material is 0.3. The modulus of elasticity is 2.06E11Pa.
Enter the Model interface, and solve the boundary conditions according to the shafting parameter settings, including the bearing position, bearing stiffness, and the mass of the propeller and large gear. Transform the mass of the propeller and the large gear into a concentrated load to act on the corresponding position of the shafting. The mass of the propeller in the water is 7493kg, and the mass of the gear is 5368kg. The final shaft alignment calculation model is shown in Figure 2.

4. Straight line alignment calculation of shaft system

4.1. Rigid support

In the statics module of the workbench, simple supports are used to support the corresponding positions of the shaft bearing support points, and the lateral and axial degrees of freedom of the propulsion shaft are limited.

4.2. Elastic support

The bearing position of the shaft system is given stiffness. In the article, the spring unit is used to simulate the bearing. Some parameters of the shaft system are: the stiffness of the rear and tail bearing is 1E9 N/m, and the stiffness of the middle and rear bearings, the intermediate bearing and the gearbox bearing are all 1E10 N/m.

4.3. Comparative analysis of calculation results

The bearing load results of finite element method linear alignment rigid support, elastic support and three-bending moment method linear alignment are shown in Table 2.
Table 2 Bearing load of linear alignment

| Bearing                  | Three-moment method (kN) | Rigid support (kN) | Deviation | Elastic support (kN) | Deviation |
|--------------------------|--------------------------|--------------------|-----------|----------------------|-----------|
| Aft stern tube bearing   | 120.39                   | 120.57             | 0.15%     | 120.51               | 0.09%     |
| Mid stern tube bearing   | 42.91                    | 43.54              | 1.46%     | 43.70                | 1.84%     |
| Fwd stern tube bearing   | 42.53                    | 42.75              | 0.52%     | 42.62                | 0.21%     |
| Mid bearing              | 25.59                    | 25.56              | 0.12%     | 25.58                | 0.04%     |
| Gear Aft bearing         | 85.43                    | 85.33              | 0.12%     | 85.42                | 0.01%     |
| Gear Fwd bearing         | 2.74                     | 2.69               | 1.82%     | 2.755                | 0.55%     |

It can be seen from Table 1 that the rigid support and elastic support bearing loads calculated by the finite element method are basically consistent with the calculation results of the three-bending moment method. The maximum deviation is within 2%. This proves the correctness of the finite element method from modeling to setting of constraints and post-processing of results; All bearing loads are positive, there is no void phenomenon in the bearing, and each bearing is subjected to the reaction force of the journal support, which meets the requirements of the bearing.

From the Figure 5 that due to the cantilever effect of the propeller, the two support methods differ in the propeller position with the largest deflection, Comparing the two cases, it can be found that the maximum displacement of the elastic support propeller is 1.8247mm below the centerline of the shafting. The maximum deformation is 1.6678mm larger than the rigid supporting propeller. Therefore, the greater the rigidity of the rear tail bearing, the smaller the droop at the propeller, and the greater the load of the rear tail bearing.

5. Optimization of Bearing Displacement and Reasonable Alignment of Shaft System

It can be seen from the straight-line alignment result of the 4.3-section shaft system that when the propulsion shaft system is in the straight-line alignment state, the load distribution of the bearing is uneven due to the cantilever action of the propeller, According to "Rules for Classification of Seagoing Steel Ships", The bearing load should not be less than 20% of the sum of all weights between two adjacent spans, and the load difference between the front and rear bearings of the gearbox should not exceed 20% of the sum of the weight of the shaft section and the large gear between the two bearings. The above requirements are not met in the straight line state, which will cause abnormal
wear at the rear bearing of the shafting, and aggravate the lateral unbalanced excitation force of the propeller, affecting the stability and reliability of the ship and the shafting operation.

The shafting installation usually takes the straight line where the tail bearing is located as the shafting reference line. In order to improve the alignment quality of the shafting, the vertical displacement of the intermediate bearing and the front and rear bearings of the gearbox relative to the shafting reference line is the independent variable. Assuming that the displacement range of the intermediate bearing and the gearbox bearing is 5mm below the axis, and the displacement of the front and rear bearings of the gearbox is the same, only the cold working condition is considered here, and the thermal expansion is not considered. The minimum value of the rear tail bearing reaction force is the objective function:

\[ \min f_1(X) = \sum A_{i1} x_i + R_{01} \quad (i = 1, 2, 3 \ldots 6) \]  

Where,
- \( R_{01} \) - The reaction force of the rear tail bearing calculated for the straight-line alignment, N;
- \( A_{i1} \) - Is the load influence coefficient, that is, the influence of the i-th bearing displacement on the reaction force of 1 unit on the rear tail bearing.
- \( x_i \) - Bearing displacement, mm.

Because of the bearing load should not be less than 20% of the sum of all weights between two adjacent spans, and the load difference between the front and rear bearings of the gearbox should not exceed 20% of the sum of the weight of the shaft section and the large gear between the two bearings, It is calculated as 12702N.

| Bearing                        | 20% minimum load (kN) | Maximum load (kN) |
|-------------------------------|-----------------------|-------------------|
| Aft stern tube bearing        | 28.01                 | 152.00            |
| Mid stern tube bearing        | 20.67                 | 68.45             |
| Fwd stern tube bearing        | 15.42                 | 64.80             |
| Mid bearing                   | 13.85                 | 63.00             |
| Gear Aft bearing              | 20.22                 | 140.23            |
| Gear Fwd bearing              | 12.70                 | 123.25            |

According to the bearing load requirements and shafting installation requirements, parameterize the displacement of the intermediate bearing and the gearbox bearing, and parameterize the load of each bearing. After parameterization, the constraint conditions can be set, as shown in the figure 6.

The optimization algorithm uses MOGA method (Multi-Objective Genetic Algorithm), It’s a variant of the popular NSGA-II (Non-dominated Sorted Genetic Algorithm-II) based on controlled elitism concepts. It supports multiple objectives and constraints and aims at finding the global optimum. In this paper, generate 16 samples initially, 16 samples per iteration and find 3 candidates in a maximum of 12 iterations. As shown in the figure 7.
Figure 7  Optimization results of bearing displacement

Through calculation, three best solutions were selected. The displacement of the intermediate bearing was 0.6mm, 1.46mm, and 1.45mm below the axis, and the displacement of the gearbox bearing was 2.66mm, 3.95mm, and 4.17mm below the axis. Using the bearing displacement result as the input condition, the three-bending moment method is used to calculate the load of each bearing, and the result is compared with the optimized bearing load. The result is shown in the figure 8.
Figure 8 Bearing load comparison

It can be seen from the figure that the three optimization results are basically consistent with the theoretical bearing load values. Only the two bearings of the gearbox have large errors, but the errors are small, and the average deviation does not exceed 5%. Figure 9 shows the deflection curve of the shafting in Option 1.

Figure 9 Reasonable shafting deflection curve for alignment (Candidate 1)

6. Conclusion

The installation quality of the ship's propulsion shafting determines the working performance of the ship's power system, as well as the quality of the ship. Based on Workbench as the calculation tool, this paper conducts static analysis on the propulsion shaft system. The simulation results are consistent with the traditional calculation results of three bending moments, which proves the correctness of the finite element model and boundary conditions. Based on the principle of genetic algorithm, the bearing displacement is optimized and solved, and the optimization result is verified by the three-bending moment method. It is concluded that the bearing displacement optimization result meets the basic requirements of shaft alignment, and the value of bearing displacement can be obtained efficiently and quickly. Has a great engineering significance.

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