Analysis and Optimization on Mechanical Properties of Stern Shaft on an Underwater Vehicle

Lei Liu[1,2](✉), Cairui Yue[1,2], Juan Wei[1,2], Zhihui Wang[1,2], and Zengwu Zhao[1,2]

[1] Beijing Institute of Precision Mechatronics and Controls, Beijing 100076, China
hlldsyll@126.com

[2] Laboratory of Aerospace Servo Actuation and Transmission, Beijing 100076, China

Abstract. Analysis and optimization of the stern shaft is of vital importance to the performance of underwater vehicles. This paper analyses the mechanical properties of the stern shaft using finite element analysis. Based on the response surface generated with samples, optimization of the bearing arrangement is considered to minimum the deformation of the shaft.

Keywords: Mechanical properties · Bearing arrangement · Underwater vehicle

1 Introduction

Stern shaft is one of the core components in the dynamic system of underwater vehicles. It links the motor with the propeller and transmits power to make the whole vehicle move forwards and backwards.

The shaft consists of diversified parts and bears variant unstable loads during the voyage of the vehicle. Thus the design of the shaft is a crucial factor for the vehicle to operate safe and sound.

Analysis on mechanical properties of the stern shaft is a necessary step during the design procedure. When the shaft is assembled as demanded state, the stress and strain in different segment should be in reasonable range. Incorrect calculation would lead to faults like over local stress, breakdown of the shaft, lower life expectancy of the bearing and failure of the sealing component [1].

Bearing arrangement is another key point during the design procedure. Span distance of the bearings would directly affect the strain, deformation and vibration of the shaft [2].

The paper studies the stern shaft of an underwater vehicle. First mechanical properties are analyzed using finite element method to obtain the mechanical parameters of the shaft. According the calculation, optimization based on response surface of the bearing arrangement is considered to minimum the deformation of the shaft.

L. Yan and J. Na (Eds.): ICFPMCE 2022, AHE 10, pp. 179–186, 2023.
https://doi.org/10.2991/978-94-6463-022-0_16

2 Analysis on Mechanical Properties

There are several methods to manipulate the analysis on mechanical properties, such as transfer matrix method, three-moment method and the finite element analysis (FEA). FEA has the advantage of higher precision and solid modelling, which makes it widely applied by researchers [3].

Solid model is established according to the actual dimension and assembly relationship. The material for the shaft and the propeller are structural steel and copper alloy. To simplify the calculation process, the propeller is modelled as a plate with the same weight. The mesh for the contact area between bearings and shaft are refined to achieve higher precision. The model after meshing can be seen in Fig. 1.

Acceleration of gravity is introduced to take the effect of the mass into account. Bearing II makes the shafting fixed in the axial direction by the interaction with the

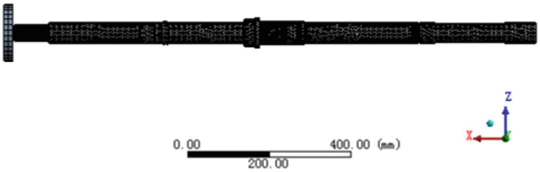


Fig. 1. Model after meshing

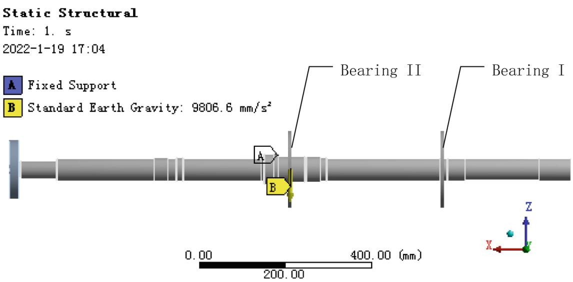
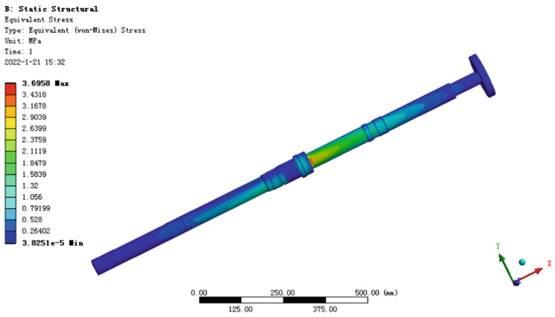


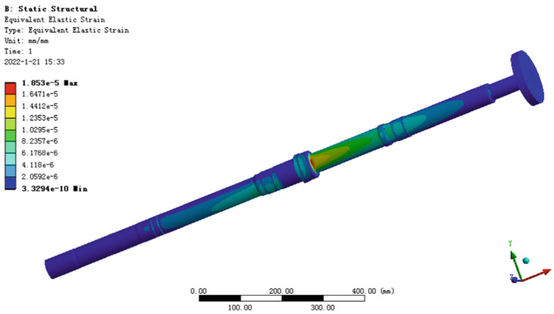
Fig. 2. Model with boundary conditions

Table 1. Result of FEA

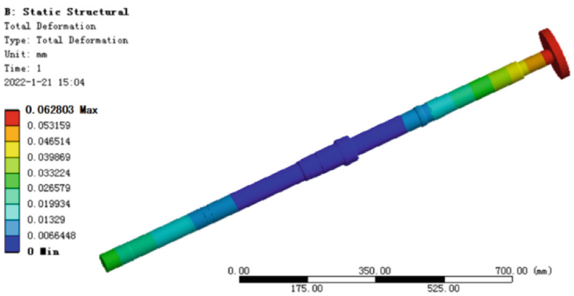
Item	Value
Supportive force of bearing I	51.5 N
Supportive force of bearing II	415.2 N
Largest stress	3.7 MPa
Largest strain	1.85×10^{-5}
Total deformation	largest at the end, 0.063 mm



a) the distribution of stress.



b) the distribution of strain



c) total deformation

Fig. 3. Result of FEA

shoulder. Thus the shoulder should be fixed. The distance between bearing I and the right end is 287.5 mm. The distance between bearing II and the right end is 617 mm. The supporting function of bearings is equivalent as springs with certain stiffness. The stiffness is defined as the following equation,

$$k = 0.177236 \cdot \frac{\cos^2 \alpha}{\sin^{1/3} \alpha} \cdot (Z^2 D_b F_v)^{1/3} \tag{1}$$

where α is the contact angle, Z and D_b are the number and diameter of the rolling elements in the bearing. F_v is the pre-tightening force [4]. The stiffness of bearing I is $k_1 = 0.9 \times 10^8$ N/m, the stiffness of bearing I is $k_2 = 1.4 \times 10^8$ N/m. Model with boundary conditions is shown in Fig. 2.

After pre-processing, numerical calculation is manipulated. The result is illustrated in Table 1 and Fig. 3. According to life expectancy calculation, the bearing can operate for 12627.7 h, satisfying the demand. Maximum strain and stress are all within the ultimate strength of the material. But the deformation at the end of shaft is 0.063 mm, which is relatively lager. Large deformation at the end would cause inefficiency of propelling, acceleration of abrasion for the sealing component.

3 Optimization of Bearing Arrangement to Minimum the Deformation

FEA shows that the deformation at the end of the shaft is large, which would cause severe troubles. As the supporting part, bearings play an important role in the deformation of shaft. Based on response surface, optimize the bearing arrangement to minimum the deformation.

3.1 Mathematical Model for Optimization

Considering the distribution of the gravity center, the distance range of bearing I is 275 mm to 300 mm, the distance range of bearing II is 600 mm to 632 mm, which make up the design space. Thus the mathematical model for the optimization can be expressed as

Solve $\mathbf{x} = (x_1, x_2)^{\mathrm{T}}$, so that

$$f(\mathbf{x}) \to \min$$

With the constraint condition

$$\mathbf{x} \in \mathbf{R}, \quad \mathbf{R} = \{(x_1, x_2) | 275 \le x_1 \le 300, \;\; 600 \le x_2 \le 632\}$$

where $\mathbf{x}$ is the distance of bearing I and bearing II, $f(\mathbf{x})$ is the deformation at the end of the shaft.

Table 2. Samples generated by DOE and the corresponding deformation

Name	x_1	x_2	$f(x)$
1	287.5	616	0.061852
2	275	616	0.060169
3	300	616	0.060168
4	287.5	600	0.066286
5	287.5	632	0.054485
6	275	600	0.066283
7	300	600	0.066282
8	275	632	0.054484
9	300	632	0.054481
10	293.77	623.97	0.057282
11	281.25	608.08	0.063144
12	293.68	607.99	0.063174
13	299.98	607.99	0.063171
14	287.48	624.01	0.057268

3.2 Optimization of Bearing Arrangement

Response surface is the function between the output parameters and the input parameters, which can demonstrate the influence of each design variable on the target parameter [5]. After the construction of response surface, estimated value in the design space can be easily obtained to do the optimization.

The accuracy of the response surface is related to the selection of samples. Accuracy improves as the amount of samples grows. On the other hand, large amount of samples would cause the calculation efficiency to drop. DOE (Design of experiment) is usually used to generate samples to construct the response surface. DOE is a statistic method to arrange experiment and analyze data which can make a reasonable arrangement for the simulation. DOE makes it possible to get the response surface with fewer samples [6]. Samples generated by the DOE and the corresponding deformation are listed in Table 2.

Second-Order polynomial is utilized to form the response surface. Second-Order polynomial is a statistical methodology to do the regression analysis, so that the relationship between two or more quantitative variables can be estimated. The response surface is shown in Fig. 4.

To validate the accuracy of the response surface, samples and the predicted value from the response surface are compared in Fig. 5. As can be seen in Fig. 5, the two values are close to each other, which means the response surface is reliable.

MOGA (multi-objective genetic algorithm) is utilized to search the optimum scheme from the response surface [7]. MOGA simulates the evolution of living beings to search for the optimum scheme. Comparing with traditional optimization algorithm, it has advantages such as higher efficiency, stronger fault-tolerant and better expansibility [8].

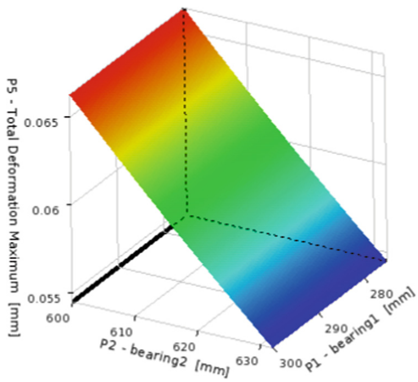


Fig. 4. Response surface

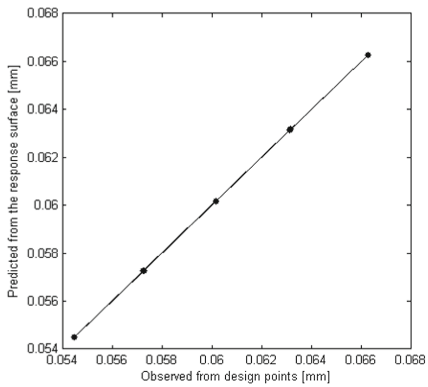


Fig. 5. Compare between the samples and the predicted value

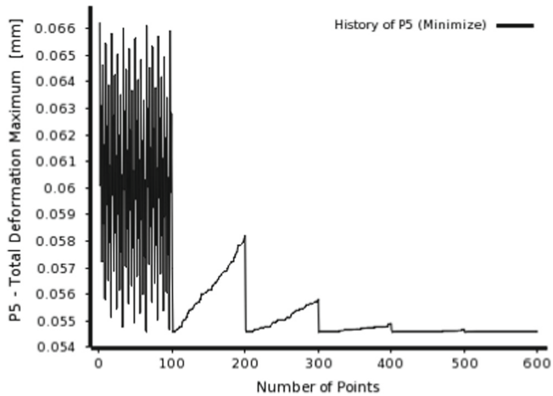


Fig. 6. Iteration process of MOGA

The searching process is illustrated in Fig. 6. The result converged after about 600 times of iteration. The solution is

$$\mathbf{x} = (291.82, 631.75)^{\mathrm{T}},\ f(\mathbf{x}) = 0.054$$

Which means when position of bearing I is 291.82 mm and bearing II is 631.75 mm, the deformation of the end is the smallest, 0.054 mm.

4 Conclusion

Mechanical properties of the stern shaft on an underwater vehicle are analyzed by FEA, showing that most mechanical parameters are within the performance limits of the material, except that the deformation at the end of shaft is large. Based on former analysis, optimization of the bearing arrangement is implemented. After the optimization, the deformation is obviously reduced. The optimized stern shaft is assembled on the underwater vehicle and has been operating without breakdown for several periods, showing that the analysis and optimization are reasonable.

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