Research Article

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Design and testing of a smart rubber stave for marine water-lubricated bearings

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Abstract: The water-lubricated bearing is mainly installed at the stern of the ship to support the rotation of the main shaft of the ship, which is an important component of the ship’s power plant. The rubber stave of the water-lubricated bearing acts as an elastic body, which can effectively suppress the rotational vibration of the rotating shaft and improve the shaft alignment effect. To monitor the operational status of the water-lubricated bearing at the stern of a ship, a design method of smart rubber stave for water-lubricated bearings is proposed in this article. According to the structure of the rubber stave, the packaging and protection form of the optical fiber, the forming process of the rubber stave, and the mechanical analysis were carried out to determine the distribution design principle of the fiber Bragg grating (FBG) in the rubber stave. Then, FBGs were packaged, protected, and implanted with an uneven distribution into the rubber stave to achieve force sensing in the bearing. With reference to the force state of the water-lubricated bearing during shipbuilding and ship operation, various types of condition monitoring tests were conducted on the smart rubber stave using an elastomer testing machine, which were to analyze the effects of load sizes, frequencies, and ambient temperatures. The tests showed that the FBGs in the rubber stave could monitor the static and dynamic loads of the bearing under the seawater environment or inland water environment below 30°C. This method can be used for the smart designing and online load condition monitoring of water-lubricated bearings.

Keywords: water-lubricated bearings, fiber Bragg gratings, condition monitoring, smart bearings

1 Introduction

Marine water-lubricated bearings are primarily installed at the stern of a ship, using water as a lubricant to support the rotation of the ship’s main shaft [1]. Due to the low viscosity of water, the formed lubricating water film is only tens of microns [2]. Under the condition of low speed and heavy load, the water film at the bottom of the bearing is easily ruptured, and friction noise occurs [3]. During the operation of the ship, the rubber stave is mainly affected by the axial vibration, whirling vibration, and frictional vibration of the ship’s main shaft [4]. The rubber stave in a water-lubricated bearing is an elastic body and so can effectively reduce the vibration of the propeller shaft and improve the shaft alignment effect [5]. At present, many scholars design various forms of ship water-lubricated bearing test benches to study the various working conditions and dynamic states of water-lubricated bearings. A variety of sensors such as temperature, pressure, vibration, and wear detection are installed on the test bench, which are primarily located on the outer shells [6], inside the shafts [7], outside the shafts [8], and on the test benches [9]. Hence, implanting sensors in the rubber stave to monitor the condition of the water-lubricated bearing will further promote the integration of the sensors and the stave, thereby making the bearings smarter.

Strain sensors are commonly used in smart rubber products to measure product deformation. Hariri et al. [10] designed flexible printed capacitive strain sensors that were pasted in the radial and circumferential directions of the tire surface, thereby obtaining the deformation state of the tire under large load. Matsuzaki et al. [11] proposed a novel rubber-based strain sensor fabricated using photolithography, overcoming the high stiffness
problem of traditional foil strain gauges and monitoring the deformation characteristics of tires accurately. Because the strain sensing element was written into the rubber matrix, the sensor had the same mechanical properties as the tire surface. However, the large areas of the strain gauges will affect the adhesion between the composite materials and shorten the fatigue life of the stave. Assuringly, fiber Bragg gratings (FBGs) are passive strain optical sensors that have the advantages of small size, softness, strong anti-interference ability, moisture resistance, and distributed measurement. Zhao et al. [12] affixed FBGs to the tread pattern of a radial tire of a vehicle, monitoring the hoop strain of the tire and calculating the bending moment of the conjugate beam method in bridge structural mechanics. In order to protect the FBG sensing element, Roveri et al. [13] pasted the FBGs to the inner surface of the vehicle tire, and drilled holes on the bottom tread of the tire for leading out the optical fiber. By monitoring the deformation of the tire, the mechanical characteristics of the tire and the ground contact process are analyzed.

From the analysis above, it can be seen that sticking FBGs on the surface of the rubber structure has the advantages of simplicity and easy distribution monitoring in detecting the deformation of the structure. Since the mechanical structure has no shrinkage, the FBGs are often embedded in the reserved grooves of the mechanical structure for vibration or temperature measurement [14,15]. However, the rubber material has strong shrinkage, and it is difficult to drill holes in which the FBGs are embedded on the rubber stave. Therefore, implanting FBGs in rubber staves for condition monitoring has three primary problems. First, during the vulcanization and molding process for a rubber stave, the vulcanization temperature reaches 160°C and the pressure reaches 15 MPa. In addition, the stave’s rubber material shrinks rapidly after cooling. So the fiber breaks easily when FBGs are directly implanted into a rubber stave without being packaged and protected [16]. Second, even though FBGs are implanted into a rubber stave, they cannot affect the stave’s support performance. At the same time, the sensing performance of the FBGs cannot be damaged. FBGs and rubber staves must be compatible with each other in the structure [17]. Third, material creep properties always affect the measurement accuracy of load cells [18], and the creep of the rubber matrix material will inevitably affect the method and accuracy of load monitoring. This article introduces a method of implanting an uneven distribution of Bragg fiber gratings into the rubber stave of a marine water-lubricated bearing and studies its condition monitoring performance through experiments.

2 Design of a smart rubber stave

There will be its own sensing characteristics when the FBG is implanted in the rubber stave of the ship’s water-lubricated bearing for structural force detection. The strain of the grating is easily affected by the optical fiber coating, the packaging structure, the isotropy of the rubber matrix material, the buried depth of the sensor, the rubber stave structure, and the ambient temperature. The encapsulation structure of the optical fiber should have a good strain transmission. Therefore, when implanting FBGs in the rubber matrix for smart design, it is not only necessary to fully consider the sensing and detection principle of FBGs, but also to design a good package for FBGs. Ultimately, the sensing elements should be reasonably distributed in the rubber stave of water-lubricated bearings.

2.1 Features of marine water-lubricated bearings

The structure of a marine water-lubricated bearing is shown in Figure 1. The bearing sinks are often accompanied by large amounts of impurities, such as sand, and are drainage channels for rubber staves’ abrasives. The structure of a rubber stave, composed of a rubber matrix and a skeleton material, is shown in Figure 2. Compared with conventional sliding bearings, water-lubricated bearings for ship stern shafts have large length-to-diameter ratios and are prone to uneven local pressures. Additionally, due to the skeleton structure in rubber staves, the rubber matrixes are more prone to experience uneven forces.

![Figure 1: Schematic diagram of a water-lubricated bearing.](image-url)
2.2 Sensing principle and package design

2.2.1 Sensing principle for FBGs

FBGs have a core structure with periodic changes in the refractive index. Their working principle is shown in Figure 3. According to the mode coupling theory [19], when broadband light is transmitted in the fiber grating, the center wavelength of the reflected light, $\lambda_B$, satisfies the following equation:

$$\lambda_B = 2n\Lambda.$$  \hspace{1cm} (1)

In equation (1), $\Lambda$ is the grating period and $n$ is the effective refractive index of the core. The light reflected for different gratings on the same fiber can be demodulated by a fiber grating demodulator to convert the optical signal into a digital signal. Changes in the temperature and pressure of the measured object cause changes in the grating period and in the center wavelength of the reflected light, as shown in Figure 4. The relationship between the center wavelength, $\lambda_B$, of the fiber grating, the temperature, $T$, and the strain, $\varepsilon$, is expressed by the following equation:

$$\frac{\Delta \lambda_B}{\lambda_B} = (a_T + \zeta)\Delta T + (1 - P_e)\Delta \varepsilon.$$ \hspace{1cm} (2)

In equation (2), $a_T = \frac{1}{\Lambda} \frac{\partial \Lambda}{\partial T}$ is the thermal expansion coefficient of the optical fiber, $\zeta = \frac{1}{n} \frac{\partial n}{\partial T}$ is the thermo-optical coefficient of the optical fiber material, and $P_e = \frac{1}{n} \frac{\partial n}{\partial \varepsilon}$ is the elastic-optical coefficient of the optical fiber material.

When the ambient temperature is constant or approximately constant, the relationship between the center wavelength of the fiber grating and the strain can be expressed by the following equation:

$$\frac{\Delta \lambda_B}{\lambda_B} = (1 - P_e)\Delta \varepsilon.$$ \hspace{1cm} (3)

Combined with the structural characteristics of a water-lubricated bearing, the FBGs can be implanted into the rubber matrix along the axis of the rubber stave. The radial loads are monitored by multi-point measurements of the axial strain in the rubber stave, as shown in Figure 5. To ensure that the center wavelengths of the FBGs distributed on the same fiber do not interfere with each other, the changes in the center wavelength must meet certain conditions:

![Figure 2: Typical structure of the rubber stave.](image)

![Figure 3: Working principle of FBGs.](image)

![Figure 4: Center wavelength shift characteristics of the reflected light.](image)
In equation (4), \( \lambda_m \) represents the initial center wavelength of the fiber grating, \( \Delta \lambda_m \) is the center wavelength offset, and the numerical subscripts represent the corresponding measurement points. The center wavelength offset for each measurement point is determined by the environmental stress.

2.2.2 Packaging design for FBGs

At present, the common methods for packaging FBGs for structural health detection refer to the surface-adhesive and ring tube methods. To reduce the influence of the FBG sensors on the mechanical properties of the rubber stave, the ring tube packaging structure was selected for this study.

When an FBG is protected by ring tube packaging, its strain detection capability will be affected. Analyzing the optical fiber packaging strain transfer process will help improve the optical fiber packaging process.

The structure of the ring tube package is shown in Figure 6(a). The length of the package is \( 2L \), and the FBG is located at the axial symmetry center of the package. Among them, \( o \) represents the optical fiber, \( f \) represents the filling layer, and \( p \) represents the package protection layer. The axially symmetric cross-section and stress distribution are shown in Figure 6(b). The origin of the coordinate system, \( O \), is set at the symmetric center of the package. Additionally, \( \sigma \) denotes the normal stress, \( \tau \) represents the shear stress, \( \varepsilon \) is the strain, \( x \) is the axial position, and \( r \) denotes the radial position.

The strain transfer relationship between the outer surface of the optical fiber and the inner surface of the package was obtained from the shear lag method [20,21]:

\[
\varepsilon_{o}(x) = \varepsilon_{p}\left(1 - \frac{\cosh(kx)}{\cosh(kL)}\right). \tag{5}
\]

The strain transfer rate is expressed by the following equation:

\[
a(x) = \frac{\varepsilon_{o}(x)}{\varepsilon_{p}} = \left(1 - \frac{\cosh(kx)}{\cosh(kL)}\right). \tag{6}
\]
Therefore, the maximum value of the strain transfer rate occurs at the axial center of the sensor:

$$a(0) = \frac{e_o(0)}{e_p} = \left(1 - \frac{1}{\cosh(kL)}\right). \quad (7)$$

The average strain transfer rate in the ring tube package is expressed by the following equation:

$$a = \frac{e_o(x)}{e_p} = \frac{2}{2L} \int_0^L e_o(x)dx = 1 - \frac{\sinh(kL)}{kL \cosh(kL)}, \quad (8)$$

The material property parameters of the optical fiber and packaging that appear in the expression for $k$ are shown in Table 1.

Equations (7)–(9) show that a large filling layer elastic modulus leads to a large average strain transfer rate, a large intermediate layer thickness leads to a small average strain transfer rate, and a long FBG package leads to a large average strain transfer rate. They also show that the center of symmetry for an FBG is the location at which the maximum strain transfer rate occurs. According to the characteristics above, the protective layer was made of 304 stainless steel tube with 0.6 mm of outer diameter and 0.1 mm of wall thickness, and the filling layer was composed of DG-4 epoxy resin.

| Material parameters | Symbols | Units |
|---------------------|---------|-------|
| Elastic modulus of the optical fiber | $E_o$ | Pa |
| Elastic modulus of the filling layer | $E_f$ | Pa |
| Shear modulus of the filling layer | $G_f$ | Pa |
| Poisson’s ratio of the filling layer | $\mu_f$ | — |

Note: $G_c = E_o/[2(1 + \mu_o)]$.

### 2.3 Distribution design for FBGs

When an FBG is detecting strain, the force of the grating must be uniform in the local range of the force. Otherwise, the reflected light spectrum of the FBG is prone to chirp (the spectrum has either multiple peaks or no peaks), and it is difficult to form an effective center wavelength. Therefore, it is necessary to analyze the forces in the rubber stave’s structure to guide the FBG distribution design. Since the stave’s base material was hard rubber, the linear elastic model, the Neo-Hookean model, and the Mooney–Rivlin model were selected for a comparative analysis, as shown in Figure 7. Based on the results, the Mooney–Rivlin rubber model was selected for the structural analysis of the rubber stave, and the rubber material parameters were $C_{01} = -1.292$ and $C_{10} = 2.596$. Additionally, the skeleton material was made of structural steel.

The static analysis results for the rubber stave are shown in Figure 8. To improve the efficiency of the computer simulation analysis, the rubber stave was simplified, according to its symmetrical structure, to 1/4 of the original stave, as shown in Figure 8(a). Additionally, to make the simulation conditions similar to the actual working conditions, the surface of the rubber stave was clamped with curved fixtures, and a pressure of 1 MPa was applied to the other side of the fixtures. The divided stave’s grid structure is shown in Figure 8(b). The grid size did not exceed 3 mm, and there were 48,533 grids and 87,965 nodes. The equivalent strain analysis results for the entire rubber stave are shown in Figure 8(c)–(f). The results are as follows: (1) the equivalent strains on both the sides of the rubber stave and on the portion of the stave where the screws were installed on the skeleton were relatively large and (2) the equivalent strain distribution in the region between the two mounting screws for the rubber stave was relatively uniform.

According to the analysis results above, in order to further analyze the radial and axial distribution design rules of the fiber grating in the rubber matrix, the radial path was set as shown in Figure 9(a). The strain distribution data on the radial path are shown in Figure 9(b). And
the results showed that the strain was relatively large in the middle portion of the path with strong strain transfer ability. To analyze the axial strain distribution trend in the rubber matrix, the axial path was set as shown in Figure 9(c). The strain distribution data on the axial path are shown in Figure 9(d). The results showed that the strain on the end-side path of the stave’s pad was larger, and its distribution was uneven. Although the strain inside the stave’s pad was smaller, its distribution was more uniform and therefore more suitable for axially arranging FBG sensors.

In summary, when FBGs are arranged axially in a rubber bearing to detect the bearing’s forces and strains, they should be placed in the region between the skeleton mounting screws to avoid the “multi-peak or no-peak” phenomenon associated with FBGs. Additionally, by adjusting the radial positions of the FBGs in the rubber matrix, the capabilities of the FBGs to detect the forces acting on the rubber stave can be altered.
3 Tests and analyses

The manufacturing process and sensing performance of the smart rubber stave of marine water-lubricated bearings are the keys to their industrial application. In this section, vulcanization molding was carried out on the smart rubber stave of water-lubricated bearing, and the multi-condition test analysis was carried out to test the encapsulation effect of FBGs composited with the rubber stave, and to study the sensing law of the smart rubber stave.

3.1 Test scheme

Two primary processes were conducted when preparing a rubber stave for the tests. First, according to the FBG packaging and distribution design rules described in Sections 2.2 and 2.3, a capillary steel pipe was implanted into the rubber stave. Second, the FBGs were placed into the capillary steel pipe and secured with epoxy resin, and the smart rubber stave was completed. The primary processes involved in implanting the FBGs into the rubber stave are shown in Figure 10. The completed rubber staves were placed on an elastomer testing machine to be tested using various loads, and a fiber grating demodulator was used to determine the state monitoring capabilities of the rubber stave.

The stave load condition monitoring test is shown in Figure 11. A curved surface fixture with a length of 200 mm was used on the mechanical testing and simulation elastomer testing machine to provide a load for the stave. A temperature control box provided a constant ambient temperature for the rubber stave. The stave static load test primarily investigated the influence of rubber creep on the load monitoring performance by changing the low-frequency step load and ambient temperature experienced by the rubber stave. The stave dynamic load test primarily simulated the dynamic ballasting process of the stave’s

Figure 9: Strain analysis of FBG distribution path in the rubber stave: (a) radial strain tracking path, (b) strain along the radial path, (c) axial strain tracking path, and (d) strain along the axial path.
rotating shaft by applying a sinusoidal fluctuation load and then monitoring the frequency and amplitude of the load.

3.2 Analysis of the static load test results

Under a rated force of 7,000 N, the static load monitoring capability of the FBGs was observed by changing the ambient temperature, as shown in Figure 12(a). Although the temperature effect was superimposed in the monitoring data to produce the center wavelength offset for the FBGs, synchronous tracking of the ambient temperature by another FBG showed that the offset affected by the temperature changed linearly, as shown in Figure 12(b). During the loading process, the rubber matrix appeared in a creep state, and the monitoring data in Figure 12(a)

Figure 10: The primary processes involved in implanting fiber gratings into the rubber stave: (a) compression vulcanization molding, (b) the rubber stave removed from the mold, (c) cutting section, and (d) finished product.

Figure 11: Load condition monitoring test for the rubber stave.
Figure 12: Static load monitoring test results: (a) measured values for a 7,000 N static load at different ambient temperatures, (b) measured values for the reference grating at different ambient temperatures, (c) various static load measurements at 30°C, (d) magnified image near the measurement zero-point at 30°C, (e) measured values for a 7,000 N/0.004 Hz rectangular wave load at 30°C, and (f) linear fitting of various load measurements at 30°C.
had a more obvious zero-point error. At ambient temperatures of 20 and 30°C, the monitoring data quickly entered a stable state. As the temperature increased, the monitoring values continued to grow, making it difficult to achieve a stable state. This showed that the creep characteristics of the rubber stave increased with increase in the temperature, thereby affecting load monitoring accuracy of the stave.

When the ambient temperature was constant at 30°C, the static load monitoring effect of the rubber stave was investigated by changing the load. As shown in Figure 12(c), as the load increased, the monitoring values continued to increase, causing difficulty in entering a stable state. This indicated that the creep characteristics of the rubber stave increased as the load increased, thereby affecting monitoring accuracy of the rubber stave. However, compared with the effect of temperature on the accuracy of the bearing monitoring data, the influence of the load on the accuracy of the bearing monitoring data was relatively small. When comparing and analyzing the trends for different static load monitoring data, it was observed that the data curves for each group first appeared to decrease rapidly and then to continuously increase after a short period of stability. The transient steady-state phase near the zero-point was amplified, as shown in Figure 12(d). Therefore, according to the brief time of stability in the curve, a 0.004 Hz rectangular wave load was used to excite the rubber stave. The falling edge
amplitude of the monitoring signal for the calibration of the force state was obtained, as shown in Figure 12(e). A piecewise linear fitting for various load measurements is shown in Figure 12(f).

### 3.3 Analysis of the dynamic load test results

When the ambient temperature was 30°C, sine wave loads of different amplitudes and frequencies were used to excite the rubber stave to test its ability to detect dynamic loads. The dynamic load monitoring test results are shown in Figure 13. When the excitation frequency was constant, as the load amplitude increased, the peak measured value also gradually increased, as shown in Figure 13(a). When the excitation amplitude was constant and the frequency varied, an increase in the load frequency caused the vibration frequency of the FBG center wavelength to increase synchronously. Additionally, as the load frequency increased, the peak measured value decreased slightly, as shown in Figure 13(b).

These test results indicated that the rubber stave had a good sensitivity to the amplitude and frequency of the dynamic load. To further study the monitoring performance of the FBGs for the dynamic load state of the stave, the peak values of the different dynamic load monitoring data at 1 Hz were linearly fitted, as shown in Figure 13(c). To study the influence of the load frequency on the monitoring performance, when the intercept was 1550.0, the 1–10 Hz monitoring data values were linearly fitted, and the slope distribution trend is shown in Figure 13(d). Although there were experimental errors in the measurement data, the observed data trend showed that with increase in the different load frequencies, the rubber matrix exhibited damping characteristics, and the slope resulting from linearly fitting the monitoring data became smaller.

### 4 Conclusions

This article proposed a method of implanting FBGs in a rubber stave for force detection in a water-lubricated bearing. By using a capillary steel tube encapsulation structure, the problem of easily breaking of FBGs during the rubber stave vulcanization molding process was solved, and the compatibility of the FBGs with the rubber matrix was improved. Additionally, the structural analysis of the rubber stave provided guidance for designing the distribution of the FBGs, which further improved the stability and sensitivity of the FBGs for condition monitoring in the bearing.

The strong creep property of the rubber matrix affected the monitoring method and accuracy of the FBGs. The static load test results showed that the method had a good static load force monitoring capability in seawater and inland river water environments below 30°C, which could be used for the installation and alignment of ship shafting. The dynamic load tests showed that the FBGs in the rubber stave could monitor the low-frequency vibration signal of the rotating shaft and evaluate the dynamic load strength of the bearing. If the resolution of the fiber grating demodulator was improved, the high-frequency cyclotron and friction vibration signals of the rotating shaft could be further detected. This study provided a new method for dynamic load identification and health detection of ship shafting.

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