RESEARCH ON A LATE-MODEL TORQUE TRANSDUCER AND ITS CALIBRATION TECHNIQUE

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Abstract: In order to obtain accurate torque measurements in harsh condition, such as underwater, a torque transducer based on fiber Bragg grating is proposed in this paper. According to optimized deformation element design and fiber Bragg grating patching tactic, the new proposed torque transducer realizes accurate torque detection with automatic compensations of temperature and bending moment as well as avoiding influences from environment. The accuracy of the torque transducer, as well as its underwater performance are tested by calibration tests both in air and in underwater environment, indicating the designed torque transducer is not only able to realize high-accurate measurements, but also can be applied in torque sensing in underwater environment.

Keywords: Torque transducer, Fiber Bragg grating, underwater environment.

1. INTRODUCTION

Torque is one of the important parameters used for monitoring the operating condition of mechanical systems. In order to obtain accurate measurements of torque, a wealth of transducers[1] are proposed including acoustic torque transducers[2-4], magnetic torque transducers[5-7], photoelectric torque transducers[8-9] and fiber based torque transducers[10-11], etc. These torque transducers have been widely used in mechanical system development, operation monitoring, quality inspection and fault diagnosis, etc. When used in harsh condition, such as in high humidity or underwater, both accuracy and stability of torque transducers are reduced. Therefore, it is needed to develop torque transducers applied in high humidity or underwater environment which are insensitive to temperature fluctuations and of low shorting risk in high humidity condition.

In this paper, a newly designed torque transducer based on fiber Bragg grating is proposed especially for torque measurements in high humidity or underwater environment. This torque transducer is of high accuracy and good stability, and owns the ability of temperature and bending moment compensation. In order to examine the performance of fiber Bragg grating based torque transducer in harsh conditions, loading tests both with standard torque device in air and in underwater environment are presented in this paper, indicating the designed torque transducer can be well used in harsh environment. We believe this work provides an important reference for the applications of the torque transducer in the harsh environments.

2. TORQUE TRANSDUCER DESIGN

The basic theory of the torque transducer is illustrated by Eq. (1).

$$\varepsilon_{45^o} = -\varepsilon_{135^o} = \frac{8M}{\pi d^3 G} \tag{1}$$

In Eq. (1), M is the torque on the shaft, d is the diameter of the shaft, $\varepsilon_{45°}$ and $\varepsilon_{135°}$ are strains in the direction of the angle 45° and 135° relative to the axis, respectively. G is the material shear modulus.

The sensing of fiber Bragg grating is according to Eq. (2).

$$\Delta\lambda = k_T \Delta T + k_\varepsilon \varepsilon \tag{2}$$

$\Delta\lambda$ is the wavelength shifting of fiber Bragg grating, ΔT is the temperature variation and ε is the strain. k_T and k_ε are the sensitivity on temperature variation and strain of fiber Bragg grating, respectively.

According to Eq. (2), temperature fluctuations will obviously influence the torque measurements of fiber Bragg grating. In order to realize automatic compensations of temperature, two fiber Bragg gratings with the same temperature sensitivity are set with the directions of 45°and 135°, as shown in Eq. (3).

$$\Delta\lambda_1 = k_T \Delta T + k_\varepsilon \varepsilon_{45^o}$$
$$\Delta\lambda_2 = k_T \Delta T + k_\varepsilon \varepsilon_{135^o} \tag{3}$$

Eq. (4) can be derived by subtractions of Eq. (3).

$$\frac{\Delta\lambda_1 - \Delta\lambda_2}{2k_\varepsilon} = \varepsilon_{45^o} \tag{4}$$

Substituting Eq. (4) into Eq. (1), the mathematical model of fiber Bragg grating based torque transducer can be obtained in Eq. (5).

$$M = \frac{\pi d^3 G(\Delta\lambda_1 - \Delta\lambda_2)}{16k_\varepsilon} \tag{5}$$

The measured torque is independent to temperature parameters, proving that the designed fiber Bragg grating

based torque transducer can eliminate the influence of temperature variation in measurements. However, the design still cannot compensate the influence induced by bending moment. Here, considering both automatic compensations of temperature and bending moment, four fiber Bragg gratings are patched on the surface of deformation element: FBG 1 and 3 are patched along the direction of 45°, and the other two are set along the direction of 135° shown in Figure 1, thus, the torque can be obtained via Eq. (6).

$$M = \frac{(\Delta\lambda_1 - \Delta\lambda_2 + \Delta\lambda_3 - \Delta\lambda_4)\pi d^3 G}{32 k_\varepsilon} \qquad (6)$$

As torque measurements can only be realized by attaching fiber Bragg gratings on deformation element, the deformation element is also the key element in torque sensing system. Considering the deformation element material is important to accuracy and stability of the torque transducer, high elastic alloy steel SZK is chosen for deformation element fabrication because of its excellent stability. Besides, this material has good corrosion resistance, thus satisfying the requirements in harsh environment. The structure of deformation element is shown in Figure 1(a), the patching tactic of fiber Bragg grating based torque transducer is shown in Figure 1(b), fiber Bragg gratings can be attached on central plane surface. Surface stress on shaft surface between two flanges should be uniform distributed. The maximum measuring range of the transducer is 20 kNm. Based on the fiber Bragg grating patching tactic as well as deformation element design and fabrication, a fiber Bragg grating based torque transducer prototype used in harsh environment was manufactured and shown in Figure 2.
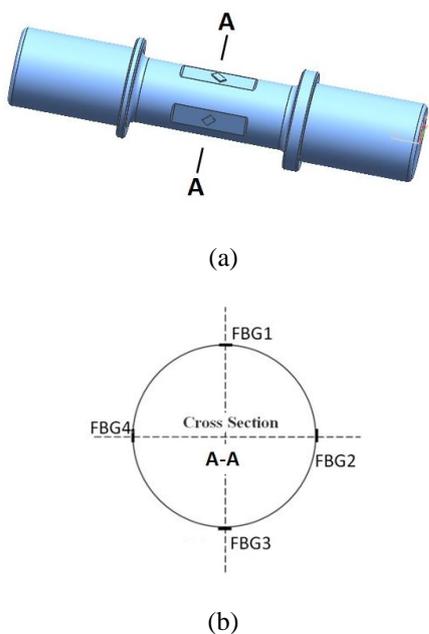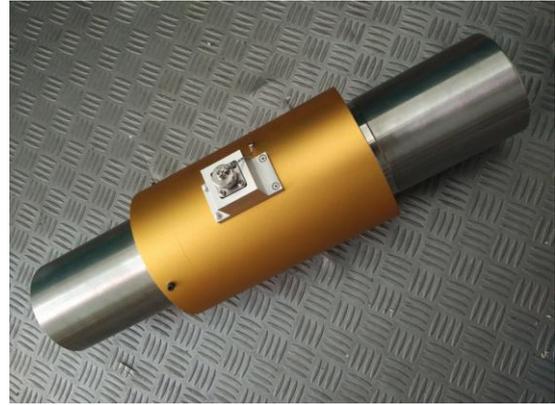

Figure 2 fiber Bragg grating based torque transducer

3. EXPERIMENTAL TESTING AND ANALYSIS

In order to test the accuracy and stability of the torque transducer, as well as its underwater performance, loading tests both in air and in underwater environment were implemented.

Firstly, loading testing with standard torque was carried out on the 50 kNm standard torque device which has the uncertainty of 0.03% (k=2) in the range between 500 Nm~50kNm. To quantitatively measure the performance of the fiber Bragg grating based torque transducer, it was loaded with standard torque from 0 to 20 kNm at 2kNm, 4kNm, 8kNm, 12kNm, 16kNm and 20kNm. The experimental procedures and data processing obey the verification regulation of static torque measuring device (JJG995-2005)[12]. Table 1 shows the data of the experiment. Additionally, quantitative analysis in Table 2 proves the torque transducer can reach class 1 fixed in the regulation.

As the proposed fiber Bragg grating based torque transducers are designed for applications in harsh environment, the conventional calibration is not enough. Here, loading tests in underwater environment were also implemented. The underwater loading testing was carried out by the device specially designed. From the fixed upper side of the device to the bottom: TT1 standard torque transducer calibrated with the German PTB delivery standards, fiber Bragg grating based torque transducer and motor were set vertically in sequence. Around the fiber Bragg grating based torque transducer, a sealed container was added to provide underwater environment. The output torque generated from the motor and magnified by speed reducer was loaded on both TT1 and fiber Bragg grating based torque transducers. Through the feedback control of the load torque by TT1 standard torque transducer, the performance of fiber Bragg grating based torque transducer can be examined quantitatively.

The performances of the fiber Bragg grating based torque transducer prototypes in both air and water are compared. From the quantitative analysis shown in Table 3 and 4, the measured torques in water by proposed transducers were consistent with the results in air. These experimental results show the presented fibre Bragg grating based torque transducer can work well in underwater environment.

(a)

(b)

Figure 1. (a) Scheme of torque transducer, (b) Designed structure of torque transducer

4. CONCLUSIONS

In this paper, a torque transducer with four symmetric fiber Bragg grating patching is proposed which is independent to temperature fluctuations and bending moment. Its accuracy and stability in torque measurements were tested by standard torque loading and loading examinations in underwater environment both for the first time. The experiments show that the measured torque values in underwater were consistent with the results in air. We believe the fiber Bragg grating based torque transducer can be potentially applied in underwater environment.

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Table1.Loading testing in air on fiber Bragg grating based torque transducer

Torque	Clockwise (nm)						
(kNm)	0º loading	0º unloading	0º loading	120º loading	120º unloading	240º loading	240º unloading
0	0.277	0.277		0.283	0.283	0.277	0.277
2	-0.136	-0.136	-0.136	-0.129	-0.129	-0.135	-0.135
4	-0.551	-0.551	-0.551	-0.543	-0.543	-0.549	-0.549
8	-1.380	-1.380	-1.379	-1.372	-1.372	-1.374	-1.375
12	-2.209	-2.209	-2.209	-2.203	-2.203	-2.198	-2.199
16	-3.037	-3.038	-3.037	-3.033	-3.033	-3.022	-3.022
20	-3.863		-3.863	-3.863		-3.847	
Torque	Counter-Clockwise (nm)						
(kNm)	0º loading	0º unloading	0º loading	120º loading	120º unloading	240º loading	240º unloading
0	0.285	0.285		0.285	0.285	0.284	0.283
2	0.701	0.701	0.701	0.702	0.701	0.700	0.700
4	1.115	1.115	1.115	1.116	1.116	1.114	1.114
8	1.944	1.945	1.944	1.945	1.946	1.944	1.945
12	2.772	2.773	2.772	2.773	2.773	2.773	2.774
16	3.601	3.601	3.601	3.600	3.601	3.603	3.603
20	4.430		4.430	4.426		4.431	

Table1.Loading testing in air on fiber Bragg grating based torque transducer

Torque (kNm)	Average (nm)	Repeatability R (%)	azimuth error R_{0t} (%)	zero error Z_r (%FS)	Delay H (%)	Error δ (%)
Clockwise (CW)						
0	/	/	/	0.00	/	/
2	-0.412	0.00	0.17		0.00	-0.41
4	-0.827	0.00	0.15		0.00	-0.05
8	-1.654	-0.06	0.19		0.00	-0.05
12	-2.482	0.00	0.26		0.00	-0.01
16	-3.310	0.00	0.28		-0.03	0.01
20	-4.137	0.00	0.28		0.00	0.00
Counter-Clockwise (CCW)						
0	/	/	/	0.00	/	/
-2	0.416	0.00	0.17		0.00	0.34
-4	0.830	0.00	0.08		0.00	0.10
-8	1.660	0.00	0.04		0.06	0.10
-12	2.488	0.00	0.04		0.04	0.02
-16	3.317	0.00	0.06		0.00	0.01
-20	4.144	0.00	0.07		0.00	-0.05

Table 3 Loading testing in air on fiber Bragg grating based torque transducer

(without water)

Torque (kNm)	Measured (nm)			Average (nm)	Error (%)	Repeatability (%)
	1	2	3			
2	0.414	0.414	0.414	0.414	0.00	0.15
4	0.829	0.828	0.828	0.828	0.10	0.18
8	1.656	1.655	1.655	1.655	0.03	0.09
12	2.483	2.482	2.483	2.483	0.01	0.03
16	3.311	3.309	3.310	3.310	0.00	0.04
20	4.137	4.137	4.137	4.137	0.00	0.01

Table 4 Loading testing in air on fiber Bragg grating based torque transducer

(loading after 2 hour in water)

Torque (kNm)	Measured (nm)			Average (nm)	Error (%)	Repeatability (%)
	1	2	3			
2	0.415	0.413	0.414	0.414	0.05	0.35
4	0.829	0.827	0.828	0.828	0.05	0.18
8	1.656	1.656	1.656	1.656	0.05	0.05
12	2.483	2.483	2.483	2.483	0.03	0.03
16	3.311	3.310	3.311	3.311	0.02	0.04
20	4.138	4.137	4.138	4.138	0.01	0.04