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RESEARCH ON STANDARD TORQUE SENSOR COMPENSATION METHOD TO MOMENT DISTURBANCE

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Abstract: High-precision torque sensor is usually used to measure torque standard machine by comparison, Torque sensor will be affected moment disturbance in the measuring process. This will affect the result of torque standard machine measurement. Flexible connections are widely used to reduce the moment interference. Compensation method by using hardware circuit can suppress the interference output of torque sensor and also get high-precision measurement result to the torque standard machine.

Keywords: Torque sensor, Comparison, Method of compensation to moment interference**.**

1. INTRODUCTION

Torque instruments are widely used in automotive, boating, and various types of power machinery manufacturing industry. In order to ensure accurate and effective of these torque instruments, these instruments usually need regular verification or calibration by torque standard equipment, such as standard torque meter, standard torque machine every year. The torque measuring instruments are usually divided into primary torque machine, torque standard machines and torque measurement instrument for general-purpose. Torque instruments should be the ultimate traceability to primary torque machines in order to guarantee the accurate torque value. The reproducibility of torque sensor output is relatively poor when torque sensor is connected to the torque machine to test directly, due to torque sensor is subjected to moment, shear force and many other factors interference in use. Flexible connections are widely used to measure the torque standard machine. In order to solve the value transfer problem of torque standard machine, we have studied the production process of the standard torque sensors and develop a high-precision standard torque sensor through the bending moment interference compensation method. The experiments showed that the direct measurement of the torque standard machine with the sensor also achieved good results; this provides a simple and effective way to solve the value transfer problem of the torque standard machine..

2. ERROR SOURCE ANALYSIS IN MEASUREMENT

2.1 Interference force analysis

Measuring the torque standard machine with torque sensor is that a same torque sensor is connected to the coupling shaft of two torque standard machine successively in measurement condition and load torque with prescribed method. When the torque sensor only respond to torque and sensor sensitive coefficient is constant during measurement, determine the torque value differences of the two torque standard machine based on the difference of the torque sensor output readings. Due to mechanical connection exist non-coaxial, asymmetric or other factors, torque sensor is not only subjected to influence of torque but also will be subjected to the interference of bending moment M, shear Q and axial force N.As shown in figure 1.

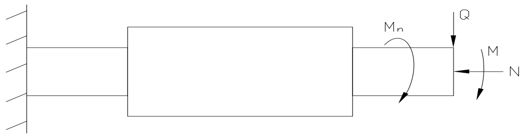


Fig.1

In this interference, the impact of moment is much than the shear and axial force. According to experience, the main interference errors are from the non-coaxial of torque sensor and torque standard machine which exist angle α. As shown in figure 2.

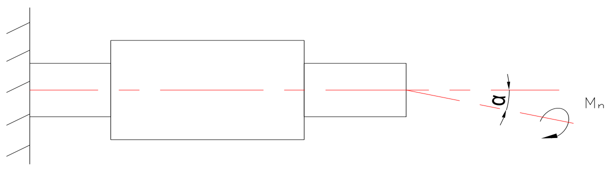


Fig.2

Where:

M_1=Mn $cos\alpha$, M_2=Mn$sin\alpha$

When α is the angle relative to the axis.

M_1=Mn$cos\alpha$=0.99985Mn,

M_2=Mn$sin\alpha$=0.0175Mn

For the ideal torque sensor, which is for torque only, as long as the angle α is less than 1 degree, the impact of these interference force on the measurement results can be ignored. But in fact, the torque sensor not only responds to the torque, there are some responses on the moment, shear and axial force. The main factor affecting the measurement results in the actual measurement was the moment, so the following analysis focused on the moment component.

2.2 Influence analysis of moment on torque sensor output

Typically, the torque sensor elastomer is designed to be a cylinder or ring. But the small range sensor is designed as a cross beam or other. In this paper, the cylinder torque sensor analyzed is shown in figure 3.

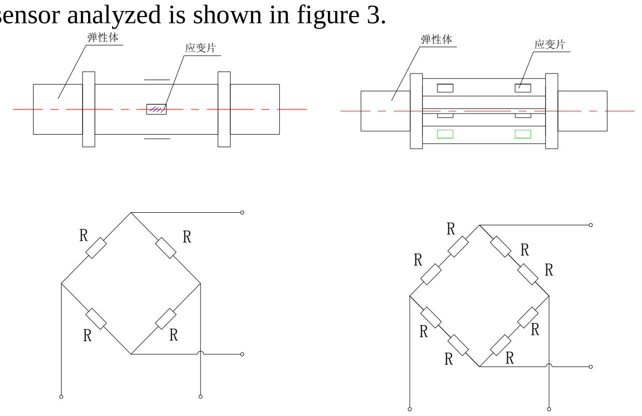


Fig.3 Structure of cylinder torque sensor.

Usually four shear strain gauges are pasted on both sides of the elastomer or around and form the Wheatstone bridge. When the sensor was subjected to influence of torque M_n and bending moment M, Sensor output S was proportional to torque M_n and bending moment M approximately.

$$S=C_1 M_n+C_2 M$$

Where, C_1, C_2 is constant.

$$C_1=\frac{16K(1+\mu)}{\pi E d^3}$$

Where E is modulus of elasticity, K is strain gauge factor. C_2 was related to the consistency of strain gauge factor, strain gauge symmetry and other production process with uncertainty.

Following analysis was the order of magnitude of C_2.

In bending moment, axis bending stress as follows:

$$\sigma_{w1}=M/W=32M/\pi d^3$$

Along the axial and tangential strain was ε_x and ε_y in strain gauge area. Due to the strain gauge was pasted on the surface of elastomer, in the plane strain state, line strain and shear strain in any directions is as follows.

$$\varepsilon_\theta=\frac{\varepsilon x+\varepsilon y}{2}+\frac{\varepsilon x-\varepsilon y}{2}\cos 2\theta+\frac{1}{2}\gamma xy\sin 2\theta$$

$$\gamma_\theta=\gamma_{xy}\cos 2\theta-(\varepsilon_x-\varepsilon_y)\sin 2\theta$$

$$\varepsilon_x=\sigma_w/E \quad \varepsilon y=-\mu\sigma_{w1}/E \quad \gamma_{xy}=0$$

$$\varepsilon_{45^\circ}=\frac{\varepsilon x+\varepsilon y}{2}=(1-\mu)\sigma_{w1}/2E$$

When the strain gauge position deviated from the 45 ° direction, assumed that the deviation angle was Δθ,

There are:

$$\varepsilon_{45^\circ+\Delta\theta}=\frac{(1-\mu)\sigma_{w1}}{2E}+\frac{(1+\mu)\sigma_{w1}}{2E}\cos 2(45+\Delta\theta)$$

$$=\frac{(1-\mu)\sigma_{w1}}{2E}+\frac{(1+\mu)\sigma_{w1}}{2E}\sin 2\Delta\theta$$

When the strain gauge position deviated from the neutral layer, assumed the deviation was Δ, bending stress in strain gauge position as follows.

$$\sigma_{w2}=\Delta\sigma_{w1}/r=32M\Delta/\pi d^3$$

$$\varepsilon_{45^\circ}=\frac{(1-\mu)}{E}\sigma_{w2}$$

$$=\frac{(1-\mu)}{E}16M\Delta/r\pi d^3$$

Considering the extreme case, it is supposed that one of the upper and lower strain gauge produced a relative 45 ° direction tilt error ±Δθ, two strain gauge pasted on the left and right produced eccentricity ±Δ which deviated to neutral layer. Extreme interference output as follows:

$$\Delta U/U=\frac{1}{4}K\left(\frac{(1+\mu)}{2E}\sigma_{W1}\sin\Delta\theta+2\frac{(1-\mu)}{2E}\frac{\Delta}{r}\sigma_{w1}\right)$$

For example, when applied moment 10kg×50cm to 2000N.m torque sensor that diameter was 42mm, σ_{w1}=65kg/cm^2 , suppose Δθ=5º, through the calculation can get:

ΔU/U=92 mV/V×10^{-5}. It is enough to affect the accuracy of measurement.

2.3 Sensor output test by interference moment

For compensation, it must do quantitative test to the moment interference output. Due to the interaction between bending moment and torsion in the testing process, so bending moment must be separated from the other factors. Through trial and error, we found the separation method and produced a moment interference testing device. Then applied some moment (about 50N.m) to torque sensor through moment interference testing device (as shown in figure 4) and measure the output.

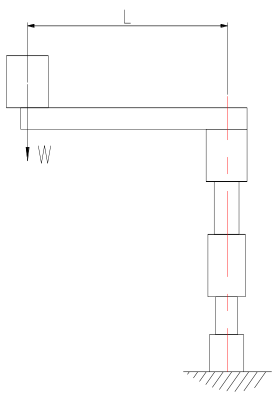


Fig.4 Moment test device

3 compensation of the output to moment interfere

3.1 Compensation method

Any bending moment M in torque sensor can be can be decomposed into two orthogonal components Mx and My, as the influence of production process and other factors cannot be perfectly symmetrical to each other to offset, The interference output generated correspondingly also can be decomposed into two components, u_1 and u_2.

u_1=AMx

u_2=B My

To compensate for two component u1, u2, a number of uniaxial strain gauges could be in orthogonal two direction of torque sensor and Mx, My correspondingly. Then connected the torque sensor to corresponding bridge arm according to certain requirements and produced the output of v_1, v_2 and u_1、 u_2 which in the same value but the opposite direction.

$$v_1 = CMx$$

$$v_2 = D\,My$$

Due to the interference output generated by the axial force and shear force of the torque sensor during measurement was far less than the output of the bending moment, ignore axial force and shear for facilitate analysis. So the output of torque sensor can be expressed as follows.

$$S = C_1M_n + AMx + B\,My + CMx + D\,My$$

$$= C1Mn + (A+C)Mx + (B+D)My$$

Where *A* , *B* can be measured through testing, *C*,*D* can be adjusted by using compensating resistance.

Obviously, as long as make A+C=0, B+D=0, compensation can be solved.

3.2 Compensation method

As moment interference output u_1,u_2 could be measured with testing, theoretically, as long as selected the appropriate resistance strain gauge connect to the bridge arm so that the output *v1*, *v2*, respectively, are offset with the *u1*、 *u2* , then achieved compensation. However, the resistance of the resistance strain gauge is usually only a few specifications to select. In order to achieve the compensation effect, adjusted the amount of compensation by the parallel resistance in uniaxial strain gauge shown in Fig.5. Assuming that R is the compensation strain gauge resistance, RP is the parallel resistance; R_{eq} is the equivalent compensator, shown in Fig.5.

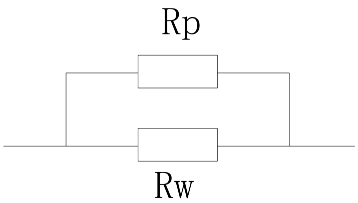


Fig.5. Equivalent resistance

$$Req = RR_P/（R+R_P）$$

When R changes to R + ΔR, accordingly Req change to Req + ΔReq.

$$\Delta Req = (R+\Delta R)R_P/(R+R_P+\Delta R) - RR_P/(R+R_P)$$

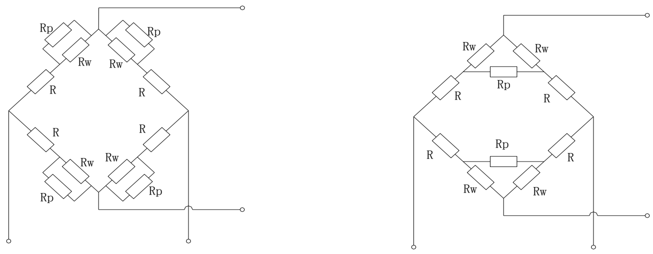
$$= \Delta R\, R_P^2/(R+R_P+\Delta R)(R+R_P)$$

As ΔR far less than R + R_P

So, $\Delta Req \approx \Delta R\, R_P^2/(R+R)^2$

As R_P / (R + R_P) is a constant, Δ*R*eq and Δ*R* approximate were linear within the scope of compensation. So with parallel method could realize linear compensation in the measuring range.

In addition, parallel compensation can be used in two ways, direct parallel and crossover parallel method (shown in Fig.6).



(a) (b)

Fig.6 Compensation circuit

The characteristic of the direct parallel compensation method is not affecting on the output of the sensor sensitive coefficient basically, but the parallel resistance should be higher. The characteristic of the crossover parallel compensation method is not changing the balance of the Bridge Road and lower compensation resistance requirements, but will reduce the output of the sensor sensitivity coefficient. We used the crossover parallel method for compensation after integrated the various factors.

Equivalent circuit of crossover parallel is shown in Fig.6. Use star-triangle conversion relations can get:

$$R_{eq1} = R_{eq2} = RR_P/（R+R_P）$$

$$R_{eq3} = R_2/（2R+R_P）$$

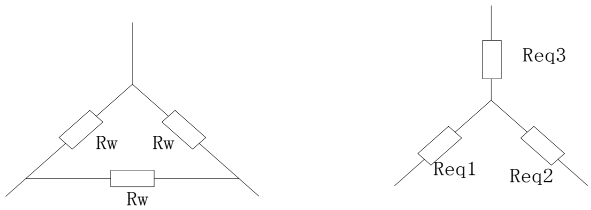


Fig. 7 Star delta conversion circuit

3.3 Compensation results

According to the analysis results, we produced some torque sensors which specification were 2000N.m (shown in Fig.8). The material of torque sensor is 40CrNiMoA. The temperature characteristics and the moment the interference output of the sensor is compensated. We have tested the torque sensor orientation performance and output of interference moment before and after compensation to the sensor output of interference moment. The results are shown in Table 1 or Fig.9.

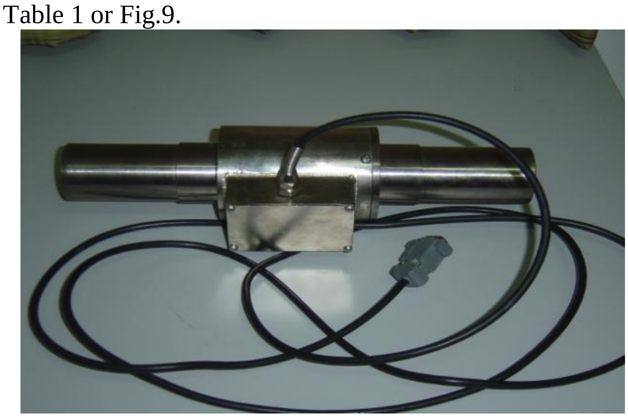


Fig.8 Torque sensor

Table.1 Interference output of moment（mV/V×10^{-5}）

		0°	90°	180°	270°
No.1	before comp.	29	-46	-27	50
	after comp.	1	7	-4	-8
No.2	before comp.	14	56	-17	57
	after comp.	0	-1	-1	1

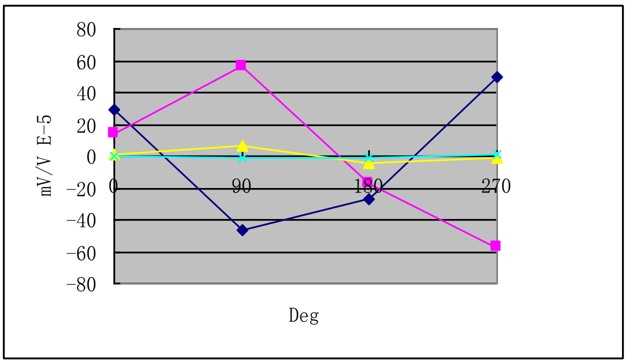


Fig.9 Compensation effect

As the result has be shown above, moment interference output of No.1 sensor from 50 mV/V×10^{-5}(before compensation) reduced to 8 mV/V×10^{-5}(after compensation), reduced by 84%. Moment interference output of No.2 sensor from 57 mV/V×10^{-5}(before compensation) reduced to 1 mV/V×10^{-5} (after compensation), reduced by 98%.

4. Test results before and after compensation

We did the moment interference test with two 2kN.m torque sensors before compensation and after compensation respectively and also test to sensor manufactured by RAUTE, the test result as shown in Table2, and tested on the torque standard machine, In addition, we also went to the China Institute of Metrology for simulation comparison with the 5kN.m torque standard machine (shown in Fig.10). Comparison result is shown in Table3.

Table.2 azimuth error of Sensor

No.1（Flat key connection）		No.2（Flat key connection）		Sensor manufactured by RAUTE（With flexible connectors）
before comp.	after comp.	before comp.	after comp.	0.046%
0.36%	0.046%	/	0.02%	

Table.3 Test data of No.1 sensor

Test point (N.m)	Output readings（mV/V×10-5）			
	ZJIM	NIM	Error %	Note：Torque standard machine（NIM）Accuracy of 0.01 class Torque standard machine（ZJIM）Accuracy of 0.1 class
100	54967	54960	0.013	
200	109948	109904	0.040	
300	164853	164858	0.003	
400	219825	219812	0.006	
500	274770	274773	0.001	
600	329734	329737	0.001	
800	439613	439683	0.016	
1000	549392	549638	0.050	

Fig.10 The testing process

5. Conclusion

From the analysis and test above, we can see that compensation method using hardware circuit can suppress the interference output of torque sensor outstandingly and make the azimuth error of torque sensor reduce from 0.4% to less than 0.05%.According to data provided by the China Institute of Metrology, reproducibility error (azimuth error) of sensor manufactured by RAUTE company is from 0.01% to 0.05% and it realized by using flexible connection in ideal connection conditions. Torque sensor developed in this project test by using a simple flat key join condition. In addition, sensor was compared with 0.01 level torque standard machine in China Institute of Metrology and 0.1 level torque standard machines in Zhejiang Province Institute of Metrology. Data show that the torque value data relative deviation of two torque standard machine is less than 0.05% in a comparable range and basically achieve the desired results.

References：

[1]J. Afeilier Experimental Stress Analysis Manual, Mechanical Industry Press. 5, 1985.
[2]Weighing Technology, 8th Conference of IMEKO Technical Committee TC-3,1980.