Improvement of the Angular-dependent Noise in a Magnetostriction Type Torque Sensor

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ABSTRACT: We proposed a new detection method for a magnetostriction-type torque sensor based on the iteration of the periodic time difference, and showed the evaluation results of its application to the rotation torque measurement of a shaft. For practical use, however, it is essential to reduce the angular-dependent noise. Therefore, we next investigated making a uniform material surface for the noise reduction. In this paper, the experimental results of the improved sensor by making the material surface uniform are described. In addition, a sensor configuration that can reduce sensor drift and hysteresis is presented. As a result, it is shown that the angular-dependent noise and sensor drift can be decreased to less than 2 bits of digital output.

KEY WORDS: (Standardized) electronics and control, physical sensor, measurement (Free) Magnetostriction, Torque Sensor

1. Introduction

We proposed a new detection method for a magnetostriction-type torque sensor based on the iteration of the periodic time difference, and showed the evaluation results for its application to the rotation torque measurement of a shaft. The features of the proposed method are as follows. (a) The method does not need a lock-in amplifier. (b) The method consists of very small-sized coils, self-excited oscillator circuits, and a microprocessor. We solved the following problems of applying this method to the rotation torque measurement of a shaft: (i) reduction of the sensor hysteresis due to the magnetic characteristic of the materials; (ii) reduction of the influence of lift-off due to the fluctuation of the distance between the sensor and the shaft; (iii) reduction of the sensor drift due to a temperature change. The proposed configuration of the sensor and nickel plating as the material surface has been a useful solution.

However, for practical use, it is essential to reduce the angular-dependent noise. Therefore, we next investigated making a uniform material surface for the noise reduction.

The target performance of the sensor is as follows. (i) The detection range of the sensor is from 0 to ±100 Nm. (ii) Hysteresis error is less than 1%. (iii) The angular dependent noise is less than 2%. (iv) The sensor drift is less than 2%.

In this paper, the experimental results of the improved sensor by making the material surface uniform are described. In addition, a sensor configuration that can reduce sensor drift and hysteresis is presented. In the experiment, a static torque adding test and a sensor ripple measurement are carried out on a carbon steel shaft (S45C) 25 mm in diameter. The output of the sensor is 8-bit digital and the full scale is ±100 Nm, which means 6x10^4 strain occurred. Authors already evaluated the sensor drift when a temperature of the atmosphere changed from 0°C to 100°C, and it was shown the proposed sensor configuration was effective in such a temperature change. In the temperature test, the characteristics against a temperature gradient occurred around the sensor coils is evaluated. A temperature gradient is generated by heating one edge of the shaft from 0°C to 30°C and the sensor output is measured under such a condition. As a result, it is shown that the angular-dependent noise and sensor drift can be decreased to less than 2 bits, which means the detection error of the sensor becomes less than ±1% for the full scale. From this result, it is shown that the sensor configuration is effective and the uniformity of the nickel plating plays an important role for improvement of the sensor.

Section 2 reviews the proposed method. Section 3 describes an angular-dependent noise that became clear from an evaluation test. Section 4 shows an improved sensor configuration. Section 5 gives experimental results of the improved sensor.

2. The Proposed Method

The sensing system shown in Figure 1 consisting of a common-use coil for driving and sensing is assumed in this paper. When the coil is driven by a pulse, the output voltage signals of the capacitor with strain and without strain are depicted as shown in Figure 2. It is understood there is a time difference between two output signals. It is also known that magnetic permeability and electric conductivity are reduced when a conductor has stress due to strain. The time difference is determined as T₁ - T₂, as shown in Figure 2, in the case of two cycles. Increasing the
number of pulse drive, the time difference will be accumulated, a
strain by input torque can be detected precisely.

In the method proposed in this paper, the self-excited
oscillator circuit with Schmidt trigger inverter depicted in Figure
3 is used to input the pulse into the sensing coil multiple times. In
this circuit, the output of Schmidt trigger inverter becomes the
driving pulse. The voltage of the capacitor and Schmidt trigger
inverter in the self-excited oscillator circuit are shown in Figure 4.
The resistance, capacitance and inductance of the circuit
determine the excited frequency. The n-th zero cross point time of
the capacitor output gives the n-th accumulated time difference.
\( T' \) in Figure 4 indicates three time accumulations.

\[
\begin{align*}
\text{Driving Pulse} & \quad R \quad L \quad C \\
\text{conductor} & \quad \text{with strain} \\
\text{without strain} & \quad T_2 \\
0 & \quad T_1 \\
V & \quad t
\end{align*}
\]

Fig. 2 Output signals of the capacitor

\[
\begin{align*}
\text{Driving Pulse} & \quad R \quad L \quad C \\
\text{conductor} & \quad \text{with strain} \\
\text{without strain} & \quad T_2 \\
0 & \quad T_1 \\
V & \quad t
\end{align*}
\]

Fig. 3 Self-excited oscillator circuit

The voltage of the capacitor and Schmidt trigger inverter in
the self-excited oscillator circuit are shown in Figure 4. The
resistance, capacitance and inductance of the circuit determine the
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\begin{align*}
\text{Capacitor Voltage} & \quad \text{Driving Pulse} \\
\text{with strain} & \quad \text{without strain} \\
0 & \quad T_2 \\
V & \quad t
\end{align*}
\]

Fig. 4 Actual measurement of the signals

3. Angular-Dependent Noise Evaluation

We evaluated the proposed method using the torque test
apparatus shown in Figure 5. Figure 6 shows the angular-
dependent noise measured by this apparatus. Measurement for
each rotational speed was carried out 6 times. The dispersion of
the sensor output is shown in Figure 6. At the low-speed range,
the greatest dispersion was approximately 18% (approximately an
average of 12%). Figure 7 indicates the experimental result in the
case of 400 rpm with a 4.8 Nm torque. The upper chart shows the
proposed sensor output, and the lower chart shows the output of
commercial product as the reference sensor. The angular-
dependent noise was equivalent to approximately 1 Nm torque.
It has been an important problem to reduce the angular-dependent noise for practical use of the proposed magnetostriction-type torque sensor. The amplitude spectrum of the sensor output with no load is given in Figure 8.

4. The Proposed Sensor Configuration Design

4.1. Sensor configuration

In general, there are two kinds of magnetostriction-type torque sensors. One is a solenoid-type and the other is a magnetic head-type. The solenoid-type can take advantage of both dispersions of a material’s magnetic characteristic and the lift-off effect. However, the embedded sensor in the solenoid-type has some disadvantages. For example, its performance decreases with a temperature change and the sensor's magnetic circuit can change easily when attaching a load at the edge of the shaft. We selected a magnetic head-type sensor consisting of small coils connected in a series to apply the advantages of the solenoid-type sensor. In the sensor, the compression detection coils and the tension detection coils are integrated. In Figure 9(a), (b) and (c), the external appearance, a piece of sensing coil with ferrite core and the development of the proposed sensor are shown, respectively. Using this configuration, the advantages of both types of sensor can be realized. Figure 10 shows the torque sensor for the experiment using the proposed coil arrangement. The coil pairs are sealed with silicon sealant to maintain a homogeneous atmosphere and reliability.

![Fig. 7 Experimental result in case of 400 rpm with 4.8 Nm torque](image)

![Fig. 8 Amplitude spectrum of the sensor output](image)

**Fig. 8** Amplitude spectrum of the sensor output (Band width 500Hz)

**Fig. 7** Experimental result in case of 400 rpm with 4.8 Nm torque

**Fig. 9 (a) External appearance of the proposed sensor**

**Fig. 9 (b) A piece of sensing coil with ferrite core**

**Fig. 9 (c) The development of the proposed sensor which consists of two lines of detection coils connected in series**

![Fig. 9 (c) The development of the proposed sensor which consists of two lines of detection coils connected in series](image)
4.2. Nickel plating on the sensor shaft

Electrolytic nickel plating can be effective in the reduction of sensor hysteresis\(^{(2)(3)}\). As mentioned above, it has been an important problem to reduce the angular-dependent noise for practical use of the proposed sensor. As one method to solve this problem, we rotated the shaft during the electrolytic nickel plating process. It was assumed that the nickel plating membrane would be generated uniformly by this method. The basic material was a carbon steel (S45C) with diameter 25 mm. The conditions of the nickel plating are given in Table 1.

Table 1 Conditions of the nickel plating process

| Condition                  | Value            |
|----------------------------|------------------|
| Plating bath pH            | 6 from 3         |
| Plating bath temperature   | 60°C from 50°C   |
| Current density            | 4 A/dm\(^2\)     |
| Average processing time    | 70 min           |
| Average thickness          | 50 μm            |

5. Experimental Results for the Proposed Sensor

The evaluation of the sensor developed above was carried out using the experimental apparatus shown in Figure 11.

Figure 12 shows the results of the static torque test for three kinds of shafts. Here, one is the shaft plated with a rotating process, the second is a non-rotating process shaft under the condition depicted in Table 1. And the third is the shaft used in the previous experiment shown at Figure 5. The test is carried out for each shaft three times. The sensor output is 8-bit digital. In this test, the output is raw numerical data in order to clear the difference of characteristic.

The sensitivity of the test shaft by the new process, which is indicated by gradient in Figure 12, is higher than that of the other test pieces. The sensitivity is 1.18–1.25 greater than that of the others. The enlarged drawing for the proposed process is shown in Figure 13. From Figure 13, maximum dispersion occurs at 30Nm and the difference against linearity is less than 2%.

To evaluate the characteristics depending on the material surface of the shaft and the angle, the sensor output at 5-degree intervals is measured, as shown in Figure 14. Measurement for each shaft is carried out 2 times. Black line shows the dispersion of sensor output of the shaft by the rotating process, and red line shows the dispersion of sensor output of the shaft by non-rotating process.

Fig. 10 Torque sensor used in the experiment

Fig. 11 Experimental apparatus for the sensor evaluation

Fig. 12 Results of the static torque test

Fig. 13 Results of the static torque test
In both processes, the maximum value of dispersion was 2 bits. Table 2 gives number of times of 1 bit dispersion and 2 bits dispersion.

Table 2  Number of dispersion

| Process                  | 1 bit | 2 bits |
|-------------------------|-------|--------|
| Rotating process        | 5     | 3      |
| Rotating Process        | 5     | 1      |
| Non-rotating process    | 14    | 6      |
| Non-rotating process    | 11    | 1      |

The frequency of occurrence in the new method of plating with shaft rotation was less than that in the conventional process.

Figure 15 shows the rotational test apparatus. The sensor output with no load at 400 rpm is given in Figure 16. In the proposed sensor, the output is converted to an analog signal by a D/A converter with width ±2.5 V (primarily 2.5 V). The output condition is the same as that of the test shown in Figure 7.

The spectrum of the signal in Figure 16 is given in Figure 17. In comparison with the spectrum in Figure 8, the maximum amplitude of the spectrum in the new process is one-half that in the conventional process.
sensor coil and the edge of shaft is almost 3 ℃. It is estimated the temperature gradient between sensor coils is occurred. In Figure 18(b), the output of the proposed sensor under this condition is given. The change of the output is less than 2 bits.

Therefore, we tested a process for producing a uniform material surface for angular-dependent noise reduction. Specifically, we tried to rotate the sensor shaft during the electrolytic nickel plating process. It was assumed that the nickel plating membrane would be generated uniformly by using this method.

In this paper, the experimental results of the improved sensor by producing the nickel plating membrane uniform were described. Also, the improved sensor configuration that can reduce the sensor drift was presented. From the experiment, it was clear that the sensitivity was improved. The basic gain became 1.25~1.3 times that in the usual sensor and the dispersions against linearity were less than 2%. From the angular-dependent noise test measured at 5-degree intervals, the maximum value of dispersions became 2 bits and the frequency of occurrence was less than that of the usual sensor. A comparison of the spectrum showed that the new process was effective. It was also shown that the drift due to the change of temperature was much improved.

5. Conclusion

We proposed a new detection method for a magnetostrictive-type torque sensor based on the iteration of the periodic time difference, and showed the evaluation results of its application to the rotation torque measurement of a shaft. However, from the viewpoint of practical use, it is essential to further reduce the angular-dependent noise.

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