Mechanics, Electronics, Automation and Automatic Control
T. Xia (Ed.)

doi:10.3233/SAEM240008

Research on the Scheme of Secondary Re-Modulation Based on Time Grating

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Abstract. This paper proposed a new type of time grating which adopts the two-stage secondary re-modulation scheme, where the output signals from the first-stage induction electrodes are applied as the excitation signals to the second-stage excitation electrodes, so that the second stage induction electrodes generate the traveling wave output signals with effective measurement period. The measurement period over the full measurement range of the sensor is increased from *N* to 2*N*, and the resolution of the sensor is doubled. The second level induction electrode adopts a differential structure design, which can effectively reduce common mode interference, improve the anti-interference ability and measurement accuracy of the sensor, and achieve high-resolution and high-precision angular displacement measurement. Experimental results have shown that this scheme can achieve high-precision displacement measurement.

Keywords. Angular displacement measurement, time grating, capacitive sensor, secondary re-modulation

1. Introduction

Angle encoders are broadly utilized in industrial automation control systems such as industrial robots, precision machine tools, and automotive manufacturing to obtain angular position information [1-3]. With the development of industrial technology, there is an increasing demand for high-precision and high-resolution angular displacement sensors. Many researchers have also invested a lot of effort in this research field. Both optical grating encoders and capacitive encoders have a wide range of applications.

The grating sensor utilizes the periodic grating line structure and the phase difference of the optical signal to measure the displacement of an object relative to its original position [4]. The grating sensors are widely used in precision measurement and control systems due to their high precision, resolution, and reliability, and are currently the most successful commercial encoders. However, the drawbacks of large size and heavy weight of grating encoders cannot be neglected, which makes it difficult for these angle sensors to be used in drone robots and portable robotic arms. In addition, as the

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sensor size decreases, the difficulty of grating sensor manufacturing will significantly increase, which undoubtedly increases the cost of gratings application [5,6].

Capacitive sensors have received increasing attention due to their simple structure, low manufacturing cost, small size, and high measurement accuracy [7,8]. However, due to the edge effects, parasitic capacitance, installation, and other factors of capacitive sensors, the nonlinear errors within the measurement period are inevitably present in measurement results. Moreover, capacitive sensors are sensitive to electromagnetic interference, which limits their application range.

This paper proposed a high-resolution and high-precision incremental time grating angular displacement sensor. The overlapping area integral method and the smoothing effect of the electric field can effectively suppress the influence of edge effects on nonlinear errors within a measurement period, this is what the traditional capacitive sensors cannot achieve [9-11]. This paper adopts the second re-modulation principle, the first stage induction output signal is loaded onto the second stage excitation electrode as an excitation signal. The measurement period over the full measurement range of the sensor is increased from N to $2N$, and the resolution of the sensor is doubled. The second level induction electrode adopts a differential structure design, which can effectively reduce common mode interference, improve the anti-interference ability and measurement accuracy of the sensor, and achieve high-resolution and high-precision angular displacement measurement. The application of the principle of secondary modulation eliminates the need for reflective rings in sensors and reduces their external dimensions.

2. Sensor design and measurement principles

The time grating sensor utilizes orthogonal electric fields to construct a highly stable and uniform motion reference frame, converting the measurement of displacement between two points in space into a measurement of time, thereby achieving the use of time to measure space. The basic structure of an angular displacement capacitive sensor based on time grating employing a two-stage secondary re-modulation scheme is illustrated in Figure 1(a). The stator substrate is equipped with the outer ring first stage fan-shaped excitation electrodes and inner ring second stage dual sinusoidal induction electrodes; the rotor substrate is equipped with the outer ring first stage dual-sinusoid-shaped induction electrodes and inner ring second stage arc-shaped excitation electrodes.

Every four adjacent fan-shaped excitation electrodes on the stator substrate are defined as the $+S$, $+C$, $-S$, and $-C$ excitation electrode sets and form a measurement period, there are a total of N measurement period within the entire measurement range. Four mutually orthogonal excitation signals with equal amplitudes and $\pi/2$ phase differences $U_{+s} = +A_m sin\omega t$, $U_{+c} = +A_m cos\omega t$, $U_{-s} = -A_m sin\omega t$ and $U_{-c} = -A_m cos\omega t$ are loaded onto the first stage $+S$, $+C$, $-S$, and $-C$ excitation electrodes to form a uniformly motion alternating electric field, and realize the conversion from displacement measurement to time measurement, where A_m is the amplitude of the excitation signal, and ω is the angular frequency.

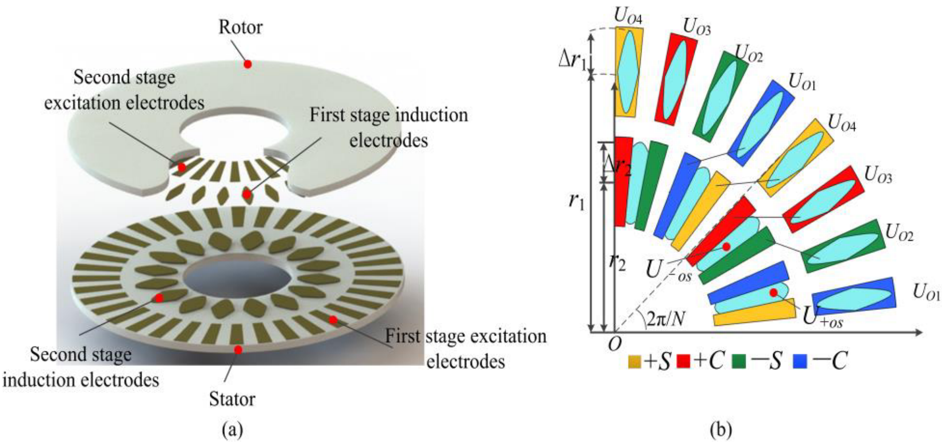

Figure 1. Schematics illustrating the proposed angular displacement time-grating sensor: (a) Basic structural model of the proposed sensor; (b)Schematic diagram of secondary re-modulation scheme.

In working condition, the output signal of the first stage induction electrodes can be expressed as

$$\begin{cases} U_{o1} = K_1 \sin(\omega t - N\theta) \\ U_{o2} = K_1 \cos(\omega t - N\theta) \\ U_{o3} = -K_1 \sin(\omega t - N\theta) \\ U_{o4} = -K_1 \cos(\omega t - N\theta) \end{cases} \tag{1}$$

Here, K_1 is the amplitude of U_{o1}, U_{o2}, U_{o3}, U_{o4}, and the magnitude of U_{o1}, U_{o2}, U_{o3}, U_{o4} varies with respect to the value of θ with a proportionality constant N. U_{o1}, U_{o2}, U_{o3}, U_{o4} are the first stage induction output signals.

The induction traveling wave signals in Eq. (1) include not only the spatial position information of the first stage, but also can be applied as the excitation signals for the second stage excitation electrodes, as illustrated in Figure 1(b). However, it must be emphasized that the loading order of the second stage excitation signal is U_{o1}, U_{o4}, U_{o3}, and U_{o2} each with a phase discrepancy of $-\pi/2$, which is opposite to the loading order of the first stage excitation signals. The second stage output signal was represented as follow.

$$\begin{aligned} U_{+os} &= 2K_1 r\Delta r \begin{Bmatrix} [1-\cos(N\theta)]\sin(\omega t - N\theta) + [1+\sin(N\theta)]\cos(\omega t - N\theta) \\ -[1+\cos(N\theta)]\sin(\omega t - N\theta) - [1-\sin(N\theta)]\cos(\omega t - N\theta) \end{Bmatrix} \\ &= -4K_1 r\Delta r \sin(\omega t - 2N\theta) \\ &= K_2 \sin(\omega t - 2N\theta) \end{aligned} \tag{2}$$

Here, $K_2 = -4K_1 r\Delta r$. As expected, output traveling wave signal varies proportionately with respect to angular displacement θ, but with a proportionately constant of $2N$. Due to the differential arrangement of the second stage induction electrode, the final output signal can be represented as

$$U_O = U_{+os} - U_{-os} = 2K_2 \sin\left(\omega t - 2N\theta\right) \tag{3}$$

This differential design facilitates the elimination of common mode interference, and improves the ability of the sensor to resist electromagnetic interference, which is beneficial for improving the measurement accuracy of the sensor. The excitation signals are emitted from the stator, and the induction signals are received from the stator. The design of the secondary re-modulation scheme avoids the use of signal reflection rings and reduces the external dimensions of the sensor.

3. Experiments

The sensor prototype was fabricated by the PCB processing, the stator and rotor were installed concentrically with a gap d=0.3 mm. The single measurement period measurement results obtained by the sensor prototype were shown in Figure 2. The maximum deviation value of a single measurement period error is about 10", the error components within the single measurement period are mainly the first-order harmonic error and fourth-order harmonic error. Among these, the first-order harmonic error is mainly caused by external interference, plate interference, and installation errors. The main cause of fourth-order harmonic error is edge effects involved with the capacitors of the sensor and the difference between the reading heads. The peak-to-peak measurement error over the full 360° range was about 15", which is slightly greater than the measurement error within a single measurement period, as shown in Figure 3. The above measurement results indicate the sensor prototype can achieve high-precision displacement measurement.

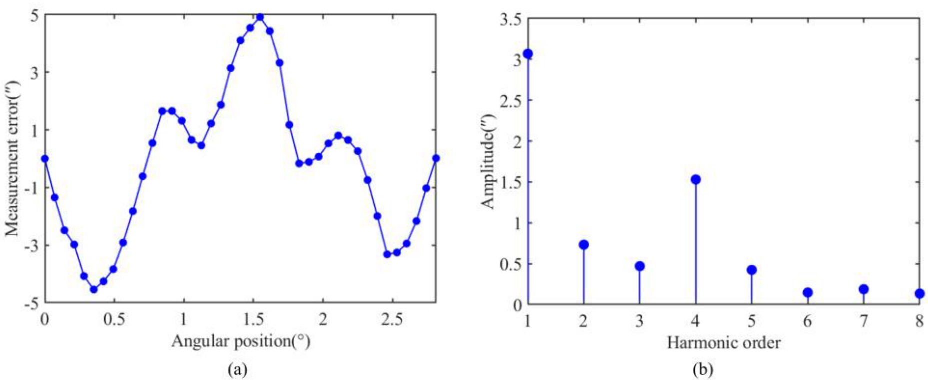

Figure 2. Measurement error within a single period: (a) measurement errors over a single measurement period of the proposed sensor; (b) the corresponding error frequency spectra.

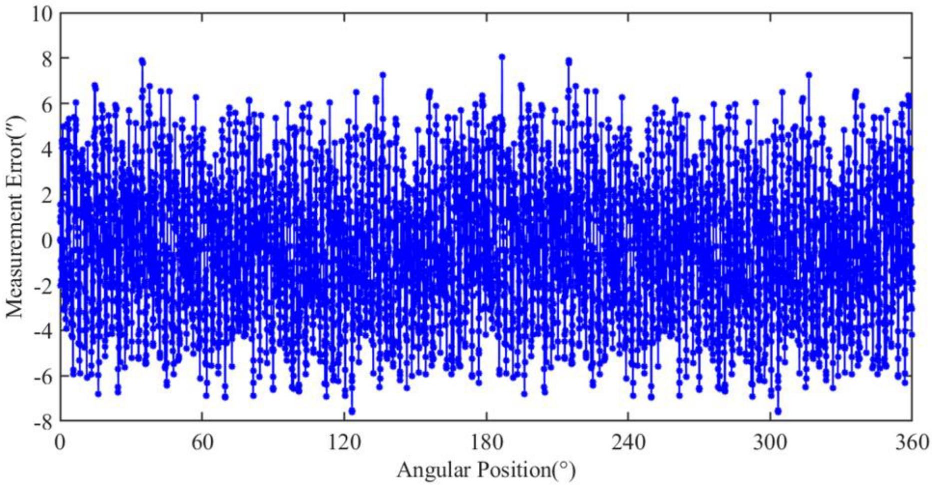

Figure 3. Measurement errors over a full 360◦ measurement range.

4. Conclusions

In this paper, the secondary re-modulation scheme based on time grating was proposed. In this scheme, the first stage induction output signal is loaded onto the second stage excitation electrode as an excitation signal. The measurement period over the full measurement range of the sensor is increased from N to $2N$, and the resolution of the sensor is doubled. The second level induction electrode adopts a differential structure design, which can effectively reduce common mode interference, improve the anti-interference ability and measurement accuracy of the sensor, and achieve high-resolution and high-precision angular displacement measurement. Experimental results have shown that this scheme can achieve high-precision displacement measurement.

References

[1] Gao, W., Kim, S. W., Bosse, H., Haitjema, H., Chen, Y. L., Lu, X. D., ... & Kunzmann, H. Measurement technologies for precision positioning, CIRP annals, 2015 June; 64(2):773-796, doi: 10.1016/j.cirp.2015.05.009.

[2] Hu, P., Guo, J., & Tan, J. An annular planar-capacitive tilt sensor with a 360° measurement range, IEEE Transactions on Industrial Electronics, 2015 Apr; 63(4):2469-2476, doi: 10.1109/tie.2015.2505673.

[3] Anandan, N., & George, B. A wide-range capacitive sensor for linear and angular displacement measurement, IEEE Transactions on Industrial Electronics, 2017 July; 64(7):5728-5737, doi: 10.1109/tie.2017.2677308.

[4] Yu, H., Jia, X., Wan, Q., Liang, L., & Zhao, C. High-resolution angular displacement technology based on varying Moiré figure phase positions, IEEE Sensors Journal, 2018 Mar; 19(6):2126-2132, doi: 10.1109/jsen.2018.2886309.

[5] Straube, Guido, et al. A heterodyne interferometer with separated beam paths for high-precision displacement and angular measurements, Nanomanufacturing and Metrology, 2021 Apr; (4):200-207, doi: 10.1007/s41871-021-00101-x.

[6] Ye, G., Liu, H., Wang, Y., Lei, B., Shi, Y., Yin, L., & Lu, B. Ratiometric-linearization-based high-precision electronic interpolator for sinusoidal optical encoders, IEEE Transactions on Industrial Electronics, 2018 Oct; 65(10):8224-8231, doi: 10.1109/tie.2018.2798568.

[7] Sauter, Thilo, Herbert Nachtnebel, and N. Kero. A smart capacitive angle sensor, IEEE Transactions on Industrial Informatics, 2005 Nov; 1(4):250-258, doi: 10.1109/tii.2005.858425.

[8] Yu, Hongxiang, Lifeng Zhang, and Mengfeng Shen. "Novel capacitive displacement sensor based on interlocking stator electrodes with sequential commutating excitation," Sensors and Actuators A: Physical, 2015 July; 230(1):94-101, doi: 10.1016/j.sna.2015.04.024.

[9] Liu, X., Zhan, B., Yu, Z., Peng, K., & Pu, H. a miniaturized capacitive absolute angular positioning sensor based on a dual two-stage secondary re-modulation scheme with time-division multiplexing, Sensors and Actuators A: Physical, 2020 Aug; 310(1):112043, doi: 10.1016/j.sna.2020.112043.

[10] Peng, K., Yu, Z., Liu, X., Chen, Z., & Pu, H. "Features of capacitive displacement sensing that provide high-accuracy measurements with reduced manufacturing precision," IEEE Transactions on Industrial Electronics, 2017 Sep; 64(9):7377-7386, 2017, doi: 10.1109/tie.2017.2698417.

[11] Zhan B, Huang P, Liu X, et al. "A Novel Self-calibration Method for Ultra-high Precision Angular Displacement Measurement", IEEE Sensors Journal, 2024 Feb; 24(3):3608-3617, doi: 10.1109/jsen.2023.3338822.