Multiturn Absolute Encoder Using Spatial Filter*

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This paper describes a vernier-type multiturn absolute encoder which uses a spatial filter to interpolate between encoder slit positions. The absolute angle can be derived from the optical encoder which uses an LED, photodiode array and coded disc consisting of three tracks. The accuracy of angular measurement for a prototype encoder was as high as $1/100\,000$, and the encoder can respond up to 3 000 rpm. The shaft revolutions are tallied by a magnetic bubble counter which uses a "memory wheel" principle to count up to 32 487 turns. No electrical energy is used to store data or count revolutions.

Key Words: Positioning, Servomechanism, Machine Tool, Robot Ultra-precision Machining, Encoder, Angular measurement, Absolute Encoder

1. Introduction

In the field of advanced factory automation, more reliable precision servomotors with multiturn absolute encoders are needed in order to increase reliability for precision machining and robotic applications. Commercially available encoders use binary coding or Gray code. This type of encoder needs a large coded disc for precision angular measurement. Moreover, it needs one additional encoder and gear to produce a multiturn signal, resulting in a relatively large, complex and expensive unit.

We have developed a vernier-type absolute multiturn encoder which uses two tracks, so the accuracy is as high as $1/10\,000$ of revolution⁽¹⁾. This multiturn absolute encoder has a magnetic bubble revolution counter. The encoder which is described in this paper is an improvement on the two-track encoder. It is smaller and simpler than conventional encoders and

more accurate than the two-track encoder.

2. Absolute Encoder

2.1 Principle of absolute angle measurement

The vernier-type encoder has three tracks. The first outer track has n slits, the second track $n-m$, and the inner third track $n-m-1$. Figure 1 shows the

Fig. 1 Configuration of the encoder

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Fig. 2 Block diagram of the encoder circuit

configuration of the encoder. There are two detectors at diametrically opposite locations. Each phase detector consists of an LED light source on one side of the disc and a photodiode array (PDA) on the other side for each track. The LED light sources in the two detectors are intensity modulated in quadrature by a sinusoidal signal. The light through the slit of the coded disc generates an intensity distribution on the PDA and is converted to photocurrent.

The principle for measuring the angle is described as follows.

The simplified block diagram of Fig. 2 shows how the phase proportional to the rotational angle of one track is measured. Each PDA consists of a group of four elements to divide the light intensity distribution into four parts. By combining signals I_1 and I_3 from a pair of elements on one PDA with signals I_2' and I_4' from the opposite PDA, a signal corresponding to phase ϕ_a of one track is obtained.

If ω is the modulation frequency, then

$$I_1 = (\cos \phi_a + 1)(\sin \omega t + 1) \quad (1)$$

$$I_2' = \left(\cos \left(\phi_a + \frac{\pi}{2} \right) + 1 \right) (\cos \omega t + 1) \quad (2)$$

$$I_3 = (\cos(\phi_a + \pi) + 1)(\sin \omega t + 1) \quad (3)$$

$$I_4' = \left(\cos \left(\phi_a + \frac{3}{2}\pi \right) + 1 \right) (\cos \omega t + 1) \quad (4)$$

$$I_c = I_1 - I_3 = 2 \cos \phi_a \sin \omega t + 2 \cos \phi_a \quad (5)$$

$$I_s = I_2' - I_4' = 2 \sin \phi_a \cos \omega t + 2 \sin \phi_a \quad (6)$$

$$V = I_c + I_s = 2 \sin(\omega t + \phi_a) + 2(\sin \phi_a + \cos \phi_a). \quad (7)$$

If the cutoff frequency for the high-pass filter in Fig. 2 is $\omega_c \gg d\phi_a/dt$, then

$$V_a = 2 \sin(\omega t + \phi_a). \quad (8)$$

Similarly, the complementary output V_a' corresponding to V_a is obtained from I_2 , I_4 , I_1' and I_3' as

Fig. 3 Principle of absolute angular measurement

$$V_a' = 2 \cos(\omega t - \phi_a). \quad (9)$$

The vernier encoder has three tracks. The outputs V_b and V_c corresponding to V_a from the 2nd and 3rd tracks can be expressed as

$$V_b = 2 \sin(\omega t + \phi_b) \quad (10)$$

$$V_c = 2 \sin(\omega t + \phi_c). \quad (11)$$

Figure 3 shows the vernier principle using the phase difference between ϕ_a , ϕ_b , and ϕ_c . The phase differences between ϕ_a and ϕ_b , and ϕ_b and ϕ_c make the vernier. They are expressed as

$$\phi_{ab} = \phi_a - \phi_b = (N_a - N_b) \cdot \theta \text{ MOD } 2\pi \quad (12)$$

$$\phi_{bc} = \phi_b - \phi_c = (N_b - N_c) \cdot \theta \text{ MOD } 2\pi \quad (13)$$

where N_a , N_b and N_c are the slit numbers for each track, and θ is the rotation angle of the coded disc. Obtaining the slit address i from P_{bc} and j from ϕ_{bc} , the shaft angle is given as

$$\theta = (i-1)\beta + (j-1)\alpha + \phi_a/N_a, \quad (14)$$

where

$$\alpha = 2\pi/N_a, \quad \beta = 2\pi/(N_a - N_b).$$

2.2 Design considerations

2.2.1 Three track method To take into consideration the non linearity of this encoder, the equation for the phase signal (7) is rewritten as follows.

$$\begin{aligned} V = & 2 \sin(\omega t + \phi_a) + 2(\sin \phi_a + \cos \phi_a) \\ & + \sum A_n(\phi_a) \sin(\omega t + n\phi_a) \\ & + \sum B_n(\phi_a) \sin(n\phi_a) \end{aligned} \quad (15)$$

As the accuracy of this encoder is described as (interpolation of slit)*(number of slits), the greater the number of slits, the less the interpolation that is needed. However, as the influence of $\sum B_n \sin(n\phi_a)$ is not negligible when the shaft rotates at high speed, increasing the number of slits causes slit address error.

To realize an accuracy of 1/100 000 of a revolution with the two-track method, it is necessary for the accuracy of interpolation to be 0.002 78 of the pitch. With the three track method, the required interpolation accuracy of 0.033 3 of the pitch is much easier to achieve.

2.2.2 Error compensation From Eq.(14), as the accuracy of this encoder is determined by ϕ_a/N_a , it needs the most accurate interpolation.

If there is an unbalance of LED intensity or assembly position offset of PDA, interpolation error would be increased. If there is an imbalance error ε in LED intensity, follows.

$$V_a = A_a \cos(\omega t + (\phi_a + X_a)) \quad (16)$$

$$V_a' = A_a \sin(\omega t - (\phi_a - X_a)) \quad (17)$$

Fig. 4 Influence of distortion on a near-sinusoidal intensity distribution

$$X_a = \tan^{-1}(-\varepsilon \sin \phi_a \cos \phi_a) \quad (\varepsilon \ll 1)$$

As is evident from these equations, the error term X_a caused by LED imbalance in intensity is cancelled out:

$$\begin{aligned} \phi &= (\phi_a + X_a) - (\phi_a - X_a + \frac{\pi}{2}) \\ &= 2\phi_a - \pi/2. \end{aligned}$$

In the same manner, the error due to the PDA assembly is also canceled out.

2.2.3 Light sources In ideal conditions, the infrared light from the LED generates a sinusoidal illuminance distribution on the PDA. As a perfect distribution of light from a source cannot be achieved in practice, the illuminance distribution has distortion; consequently it causes interpolation error.

Figure 4 shows the relationship between distribution error (optical distortion) and interpolation error. An optical diffuser, high-intensity near-infrared LEDs ($\lambda=880$ nm) with a wide angle of radiation and LED masks are used in this encoder to provide a near sinusoidal light intensity distribution (Fig. 5).

A distortion of -54 dB or less is obtained with this combination.

2.2.4 Photodiode array (PDA) Figure 6 shows a photograph of the PDA developed for this encoder. Five groups of four adjacent PDA elements corresponding to one slit pitch on the coded disc are connected together to configure one spatial filter. This filter reduces the influence of optical distortion and

Fig. 5 Light source

Fig. 6 Photodiode array chip

non uniformity in PDA sensitivity. With the exception of the photosensitive part, the PDA's surface is covered with an aluminum thin film to reduce photocurrent noise. This PDA is made of low-impurity density Si wafer (10^{13} stms/cm³), so the capacitance of the junction is low, Uniform sensitivity is required for low distortion, as discussed above. The sensitivity variation between groups of PDAs is less than 0.5%; the junction capacitance of the PDA is 22 pF/mm².

2.2.5 Coded disc The coded disc must be both compact and accurate. This coded disc has three tracks with 180, 165 and 164 slits. The accuracy of the slit directly affects the accuracy of the encoder, since the slits in the coded disc represent angular graduations. The coded disc was made using a "vector-scan direct electron beam exposure system" fabricated for this encoder⁽²⁾. Figure 7 is a photograph of the coded disc. The accuracy of the slit pattern was $\pm 0.15 \mu\text{m}$ or less.

2.2.6 Construction of encoder Figure 8 shows the construction of a prototype encoder. A hollow shaft is used to facilitate alignment with the motor, which can be a problem for a precision encoder. The eccentricity of the coded disc with respect

Fig. 7 Coded disc

Fig. 8 Construction of the encoder

to the rotational axis is adjusted to $1 \mu\text{m}$ or less. The PDA is mounted on a ceramic plate with a low coefficient of thermal expansion. The revolution counter is attached to the rear of the encoder.

2.3 Experimental results

Figure 9 shows the one-pitch linearity (linearity of interpolation between slits) and the one-turn linearity (accuracy of measuring angle of one-turn) of the prototype encoder. The one-pitch linearity was 1/1111 of pitch and the one-turn linearity was 1/150 000 of a revolution. The accuracy of the encoder meets the target of 1/100 000 of a revolution, and this is achieved by using the three-track method with low optical distortion.

Figure 10 shows the temperature characteristic of this encoder. Since the phase error is canceled out, the phase error is almost independent of temperature, as discussed under "Error compensation". Table 1 summarizes the characteristics of the prototype encoder (single-turn section only).

3. Revolution Counter Using Magnetic Bubble Device

3.1 Construction of revolution counter

Figure 11 shows the fundamental construction of

Fig. 9 Linearity of encoder

Fig. 10 Temperature characteristics

the revolution counter. It consists of four elements ; a magnetic bubble device, bias magnet, ring magnet and bubble drive coil (X-Y coil). The rotation of the ring magnet generates a rotational magnetic field on the magnetic device. The bias magnet holds the magnetic bubble, and the X-Y coil is used to read out the rotational signal.

Figure 12 shows the layout of the magnetic bubble device. The propagation patterns made by permalloy thin film are formed on the garnet film grown on the gadolinium gallium garnet (GGG) wafer. The propagation pattern consists of three loops. Each loop of the propagation pattern has magnetoresistive sensors that detect the existence of bubbles. Figure 13 shows a photograph of the magnetic bubble device.

3.2 Principle of revolution counter

Magnetic bubbles in the garnet film are transferred bit by bit in both directions along propagation patterns, which are made from permalloy thin film, by

Table 1

Resolution	1/360,000 of rev. (3.6 arc-s)
Accuracy	1/100,000 of rev. (13 arc-s)
Response	3000 rpm
Diameter	70 mm
Length	79mm (rev. counter; 30mm)

Fig. 11 Construction of revolution counter

Fig. 12 Construction of magnetic bubble device

a magnetic field parallel to the garnet film. Three shift registers, consisting of 49, 51, and 52 (mutually prime) propagation patterns, respectively, are used to count up/down revolution numbers of magnetic field. Specific bit patterns are written in magnetic bubble shift registers following the principle of a 'memory wheel'.

Figure 14 shows the block diagram of the circuit used to obtain the revolution count of the magnetic field. The total the revolution counts in the bit patterns of each of the three loops. This revolution counter can count up to 129 948 (49*51*52) using only 152 (49+51+52) propagation patterns.

If the magnetic field rotates only once per shaft rotation, the revolution counter must have the same angular accuracy as the encoder at the changeover point that causes the bit pattern to shift up or down one count. To avoid this difficulty, four magnetic field rotations per one shaft rotation were adopted, and the count up/down angle was discriminated using the encoder output angle. In this revolution counter, the

Fig. 13 Magnetic bubble chip

Fig. 14 Block diagram of the circuit

ring magnet has eight poles to keep the locus of the rotational magnetic vectors close to a true circle. Consequently, up to 32487 (129948/4) shaft revolutions can be counted.

4. Conclusions

To realize a multiturn absolute encoder, three key elements were developed. They were an ultra-precise coded disc, a PDA and a magnetic bubble shift counter with a memory wheel bit pattern. Compared with conventional multiturn absolute encoders using Gray-coded disc and gears, this vernier encoder with

the magnetic bubble revolution counter is simpler in construction, more compact and more accurate.

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