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Design and Fabrication of High Resolution Diffractive Optical Encoder

Yi-Cheng Chen*,** and Sheng-Chih Shen*

Keywords： opto-electronic encoder, Rotary absolute encoder, Diffraction grating, Optical code disc, Laser diode (LD), Photo detector array (PDA).

ABSTRACT

Rotary encoders are angular measurement devices that are used in many industrial applications. High-precision angle measurement technology is the basis for servomotor functionality; it determines the capabilities of semiconductor processing, ultra-precision machining, and precision alignment. The present study adopted an optical pickup scheme and, by generating an incident beam on a grating's narrow structure, used the diffraction phenomenon to develop a high-precision absolute optical encoder for solving the problem of signal to noise ratio (SNR) reduction due to code disc shrinkage in geometric optical designs. Experimental results prove that the structure of the diffractive optical encoder proposed in the present study can achieve a resolution of 14 bit/rev; with the addition of a two-dimensional or binary sine-wave grating design, signal subdivision technology can be used to further improve the signal resolution to 10–12 bit/rev, thus achieving ultra-high precision measurement.

INTRODUCTION

Opto-electronic encoders, which use gratings or diffraction structures to measure angles, have been applied in various fields. Conventionally, measurement techniques involving Moiré fringe gratings disregard the diffraction effect of the gratings. However, in response to reduced periods in ruled gratings, Germany, Japan, the United Kingdom, and other countries have worked diligently in recent years to break through the restrictions caused by geometric Moire fringes in high-precision nanometer measurements. Accordingly, opto-electronic encoders have been developed based on high-performance angular measurement of diffraction gratings.High-precision grating measurement technology has become a major bottleneck in the development of precision machinery; hence, research on angle measurement systems based on diffraction gratings merits further exploration.

A conventional optical rotary encoder comprises a rotatable scale, a code disc composed of glass or plastic with transparent and opaque areas, a fixed scale, a light source to illuminate the code disc, and a photodetector array (PDA) [1]. To avoid adverse effects caused by diffraction, which limit the achievable resolution, a partial solution is to move the fixed scale closer to the rotatable disc to reduce the effects of diffraction (which tend to increase with increasing optical path length), at the cost of expensive tight mechanical tolerances [2].

To meet the increasing demand for high resolution, numerous diffractive optical encoders have been proposed. Some are grating interference encoders that determine variations in the position and velocity of the shaft by detecting interference fringes [3-7]. For example, Lin used a high-density grating to direct a beam and measured the Doppler phase shift of a moving object to determine the object's velocity [3]. Koji employed a half-silvered mirror to mix light beams from a coherent source. The beams are reflected and diffracted by the encoder scale to generate interference fringes, which are related to the position of the encoder scale [4]. Lee proposed a diffractive laser encoder that allowed for high alignment tolerance by taking advantage of the preservation of parallelism between the incident and the diffracted beams; the success of that encoder was attributed to a built-in folded telescope and a grating [5]. Huang presented a simple system based on polarization interference optics and angular errors that simultaneously measured the motion errors in three degrees of freedom for a single-axis linear moving platform [6]. To reduce the system size, Ko adopted an optical pickup scheme that generated an incident beam on a moving grating and thus generated interference fringes simultaneously [7]. The aforementioned optical encoders, however, were based on the high contrast of interference fringes and relied on precise assembly of many devices, which significantly limited their achievable resolution. The bulky nature and high packaging cost of these encoders prevent their use in

Paper Received January, 2018. Revised March, 2018. Accepted April, 2018. Author for Correspondence: Yi-Cheng Chen.
**.Professor, Department of Systems and Naval Mechatronic Engineering, National Cheng Kung University, Tainan, Taiwan 701, ROC.*
***.Manager, Intelligent Mechatronics Department, Smart Micro-systems Technology Center, Industrial Technology Research Institute*

some applications [8]. In 2007, Mayer introduced an angle encoder based on a grayscale encoder, modeled on an optical pickup-based mechanism [9,10]; its principle was as follows: a laser diode source emitted a Gaussian beam into a phase grating (formed by a transparent groove), in which the first reflection order of the grating region was read out on the PD array. The distribution of the tracks on the disc was a pseudo-grayscale geometrical structure composed of different grating periods (e.g., eight paths, which defined 256 angular positions, with a resolution of 1.4 degrees). The distribution of the first diffraction order at different positions on the detector directly indicated the absolute angle represented.

DESIGN OF ABSOLUTE DIFFRACTIVE OPTICAL ENCODER

The overall architecture of the optical encoder presented in this study is shown in Fig. 1. First, a laser diode (LD) with a condenser lens provides the diffraction grating with a sufficient amount of light flux and a light beam of suitable size; the light is incident on the optical encoder disc. The optical encoder disc is designed with a plurality of microscopic grating stripes radially arranged to reflect the incident laser light in a diffractive manner to a corresponding PDA. Micro grating stripes use binary phase grating structure coding; the principle is as follows: an LD source of light emits a Gaussian beam of light striking a reflective metal grating (formed of metal stripes); the signal changes of the n^{th} reflection order of the grating region can be read on the PDA. The code structure distribution on the optical encoder differs greatly from the conventional gray-scale geometrical structure and can increase the optical resolution to 14 bit/rev.

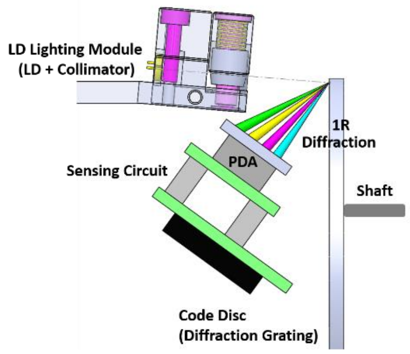


Fig. 1 Overall structure of the diffractive optical encode

The proposed optical encoder disc has a diameter of only 56 mm. It offers the advantages of miniaturization. In contrast to conventional geometric optical encoders, for which a 14 bit resolution is considered high, the grating width of the radial alignment is only 10 μm, meaning that the adjacent light beams are likely to interfere with each other in the PDA. However, the smaller the diffracting object is, the wider the resulting diffraction angles are.

The present study uses diffractive optics to break through the technical barriers of conventional geometric optical encoders.

DESIGN OF ABSOLUTE DIFFRACTION GRATING

The entire opto-electronic encoder is a reflective off-axis system, which consists of an LD, a condenser lens set, an optical encoder disc, and a PDA. Fig. 2 shows the distribution of each order of reflection after the use of ZEMAX, which simulates the incident light through the condenser lens set and the optical encoder disc. The LD uses a 404 nm coherent light source with a divergence angle of about 28° (Object NA is approximately 0.24); The light beam is collimated by passing through a collimator composed of an aspheric front surface and a cylindrical back surface. This 3 mm thick singlet is 6 mm from the laser diode and 12 mm from the disc. On the disc, the gratings are located 27~28 mm from the center of the disc. The orientation and pitch of each grating is defined according to two values. The first value is the distance (= 23.5 mm) between the disc and the PDA. The other value (= 2.3 mm) is the spacing between two adjacent photo-diodes of the PDA. These gratings (about 200 ~ 250 nm in depth and 0.5~1.0 μm in pitch) are designed to use chrome-plated mask process.

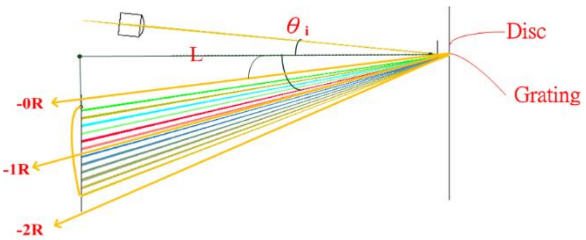


Fig. 2 Distribution pattern of 0R, −1R, and −2R order of reflection (θ_i is the angle of incidence, and L is the image distance) after the incident light passes through the focusing lens and the optical code disc.

During optical path simulation, several conditions should be considered:

(a) LD divergence for full width at half maximum (FWHM) can reach 28° due to the high resolution requirement, the light beam incident on the disc metal stripes must be as close as possible to the diffraction limit; however, a consequential problem is that when the reflected light reaches the side of the detection area, it can easily be too large to be resolved;

(b) Focusing lenses must consider manufacturability, mainly because the component diameter is remarkably small, and to have excellent focusing, an aspherical second surface may be required;

(c) The surface of the optical code disc has a layer of protective glass, and during the simulation its thickness and material should be accounted for;

(d) When the optical simulation path reflects the grating, it only picks up its n^{th} order of reflection; the arrangement of the relevant components must incorporate the remaining diffraction order, (including the zeroth order), so as to not allow stray light into the PDA;

(e) The LD and the focusing lenses have a non-normal incidence over the optical code disc, an appropriate grating period, and an appropriate orientation; furthermore, the incident angle distribution can increase the efficiency of the n^{th} reflection order. The problem of optical noise caused by the remaining diffraction orders can be reduced.

The conceptual design of diffraction grating patterns is shown in Fig. 3. The relation between incident angle and diffraction cycle can be predicted well with the grating formula. Based on momentum conservation, the diffraction grating equation can be written as follows:

$$k_0 sin\theta_d = k_0 sin\theta \cdot cos\varphi + \frac{2m\pi}{\Lambda_x} \qquad (1)$$

where θ is the angle of incidence for a wavevector k_0 with respect to the Z-axis, which is the normal of the code disc; φ represents the azimuth angle of the incidence plane with respect to the X-axis. θ_d represents the diffractive angle of the m^{th} order and Λ_x is the grating pitch along the X-axis. Since the system is an off-axis one, the above formula only provides the initial design parameters of gratings. A more precise models requires the assistance of ZEMAX to find out the relation between the position of the photo-diodes and the cycle and orientation gratings. For example, to project the first order spot onto the location of the P16 photodiode (Fig. 8b), the grating pitch and orientation are 0.56 micron and 6.05°. The main fabrication error is the linewidth of grating line, which is usually smaller than 0.02 micron due to the high precision chrome mask process and has little impact on the spot distribution.

The grating structure on the surface of the optical code disc has a track of nine grating periods (numbered T1 to T7 from inner to outer rings, Ts and Tc) in the radial direction; it is perceived as a single unit, with a total of 16,384 units in a circle. The Ts and Tc tracks within each unit are reserved for the future development of signal interpolation techniques. The seven tracks of each unit differentiate the rotation direction of the optical code disc through the combination of 28 grating intervals and angular changes from four different grating periods on the PDA row (code: 1–4), and seven different grating orientation on the PDA column (code: A–H). The diffraction spots of −1R order can correspond to 7 × 4 PDAs at the sensing end. Therefore, the detection end produces $4^7 = 2^{14} = 16{,}384$ groups of encoded positions per revolution; an absolute resolution of 14 bit/rev. can be achieved in the optical encoding section.

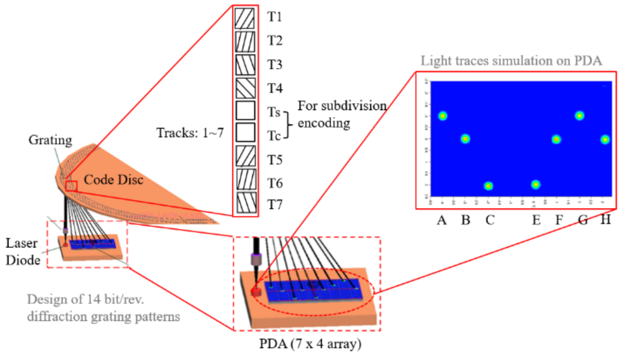


Fig. 3 Design of 14 bit/rev diffraction grating patterns

When calculated with an optical code disc with a diameter of 56 mm, the grating width of each unit cell is only 10 μm. The diffraction limit is close to the same order of magnitude as the size of this type of Airy Disk under the projected beam. However, the feasibility of its fabrication is still high. When applied to angle sensing, the number of codes available and the angular resolution can respectively amount to:

$$\frac{2\times 28\times 1000}{10} \approx 2^{14} \qquad (2)$$

$$\frac{360°}{2^{14}} \approx 0.022° \qquad (3)$$

The designs of the period and orientation of the grating stripes in each unit track all account for the relative positions of the −1R reflection order and the PDA. At the same time, the −1R reflection order light spot generated by each unit should not overlap with the 0R and −2R spots. Due to the blank area between the gratings, when a shaped Gaussian beam with a size of 10 μm (width) × 200 μm (length) is incident on the grating, the highest diffraction intensity is obtained when the center of the spot corresponds to the center of the grating. Fig. 4 shows the highest diffraction intensity detected by the PDA, decoded after the signal is digitalized, so that the device can solve the rotation angle.

The encoding principle is to provide the diffraction spots on the target locations of encoding photo-diodes. The projected spots distribution and intensities are further as the decoding basis of rotary angle. The angle position θ is consisted of absolute angle θ_a and subdivision value θ_s,

$$\theta = \theta_a + \theta_s \qquad (4)$$

In most situations, the illumination spot locates between two adjacent encoding stripes and generate eight spots for absolute encoding. Since six of the seven gratings in the two stripes are the same, it can generate six spots with the highest normalized intensities on the corresponding photodiodes. The remaining two spots are not equal and less than their normalized intensities. The distribution of the spot with higher normalized intensity along with the six spots with the highest normalized intensities is used to determine the absolute angle θ_a. To further obtain the subdivision value θ_s, a sequence of sinusoidal signals is necessary. The gratings of Ts and Tc provide these sinusoidal intensities. The signals has a phase difference of π/2 in sequence. Subdivision value is calculated by the phase shift P as following,

$$\theta_s = \frac{P}{2\pi} A \tag{5}$$

The experiment results correspond well with the sign as shown in Fig. 8a. The main deviation error of the spots' position is from the assembly precision error.

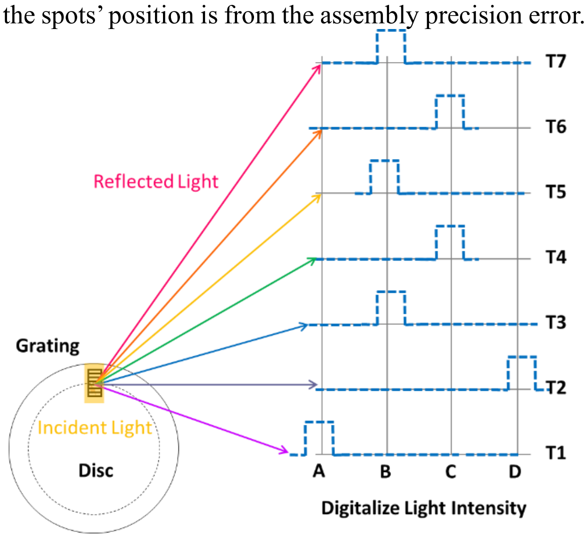


Fig. 4 When a blank area exists between the gratings, the energy of the primary diffraction order (−1R) can be detected by the PDA; this requires the shaped light source to be incident, so that the device can decode the rotation angle.

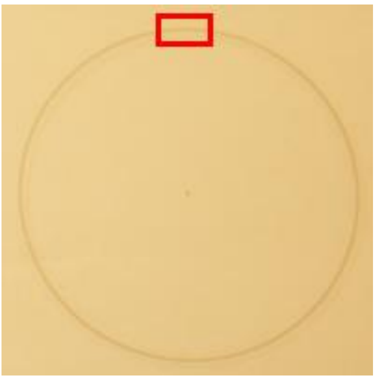
FABRICATION AND MEASUREMENT

In the present study, the optical code disc was used during the development phase to carry out a signal verification of the light diffraction to the PDA position. The material used for this binary phase grating was a chrome mask; this type of mask is often used in semiconductor manufacturing process (the theoretically definable minimum period is limited by the processing accuracy of the electron beam machine). Fig. 5 presents the grating mask (5a) and a partial magnification of the grating distribution pattern (5b and c). Fig. 6 displays the measurement keys designed specifically for the verification of the periods of the grating stripes, which were distributed at 0°, 90°, 180°, and 270° of the mask, and the measurements were determined to be 0.4997 μm, 0.5012 μm, 0.4988 μm, and 0.5004 μm, respectively.

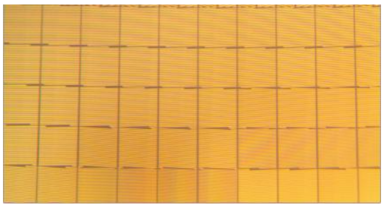
Fig. 7 displays the architecture of the optical code disc, including the diffraction grating stripes, the LD lighting module that contains the focusing lens, and the PDA placed in the positioning mechanism. The LD lighting module extends the y-axis for image-distance (L) adjustment; the biaxial mobile platform (x-axis, y-axis) is used for precise positioning of the light-receiving surface of the PDA.

After the LD light source has been diffracted through the optical code disc, its absolute-position-coded optical signal is detected by the PDA. The tiny current signal generated by the PDA generates a voltage signal through a high-sensitivity Trans-impedance Amplifier (TIA); it amplifies the signal with a Limiting Amplifier (LA), and outputs the signal to an Analog-to-digital Converter (ADC); then it decodes the digital data to calculate the angle information. Fig. 8(a) shows the actual image of the light spot position on the PDA obtained when the code disc rotates nearly 180 degrees. The code corresponding to the spot in the figure is 8202. Fig. 8 (b) presents the theoretical point with the code number 8202 and its corresponding angle (180.2197 degrees); Fig. 8 (c) shows the measurement results of the PDA detection signal at the viewpoint of the ADC. In contrast to Fig. 8 (b), the light spot distribution on the imaging surface of the PDA is equivalent to the code quality of the design, which is in line with the expected design. The tracks between the columns C and E of Figs. 8 (a) and (b) are space reserved for the future design of binary sinusoidal gratings; this enables using the PDA to detect changes in the energy of the reflection order and increasing the 10–12 bit/rev signal resolution through signal interpolation techniques.

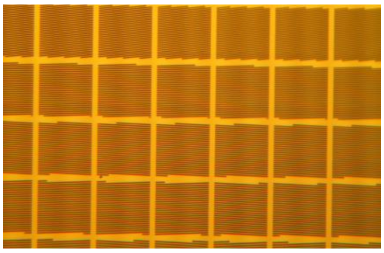
From the proto-type, we come to know this. To have the design work well, the grating efficiencies and assembly precision have to be precisely controlled. The grating efficiency is a function of grating linewidth and depth. Previous simulations show that as linewidth and depth is 0.5 micron and 200 nm, the tolerances are less than 0.02micron and 30 nm, respectively, which unavoidable requires a highly precise chrome mask process. The main assembly errors include the decentration and tilt of beam-shaping singlet. The singlet is to provide a rectangular spot with a width close to diffraction limit. Therefore, any error easily broadens the width of the rectangular spot. In practice, the installation precision of current setup needs further improvement. The best rectangular spot measured in our setup is 14.4 μm × 147.1 μm, which is much worse than the design target 10 μm × 200 μm. This assembly error further reduces the uniformity of the illumination rectangular spot. When the illumination rectangular spot is not uniform and out-of-size, each gratings in the same stripe receives different intensity, which also induces diffraction spots with different intensities. Since the intensity and distribution of diffraction spots are not as good as expected due to design and assembly errors, further improvement of the setup should be performed for further meaningful investigation of absolute and subdivision signals.



(a)

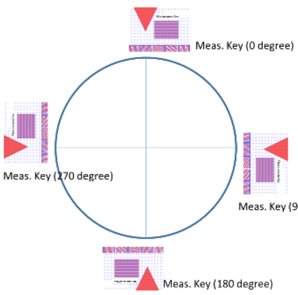


(b)



(c)

Fig. 5 (a) Grating mask; (b) partially magnified 100× grating distribution pattern; (c) partially magnified 500× grating distribution pattern.



Unit: um

Meas. Key	Clear / Dark	Deviation (Clear)	Deviation (Dark)	Period
0 degree	0.25 / 0.25	-0.0035	+0.0032	0.4997
90 degree	0.25 / 0.25	-0.0024	+0.0036	0.5012
180 degree	0.25 / 0.25	-0.0019	+0.0007	0.4988
270 degree	0.25 / 0.25	+0.0029	-0.0025	0.5004

Fig. 6 Grating stripes period measurement keys (design value of 0.5 μm)

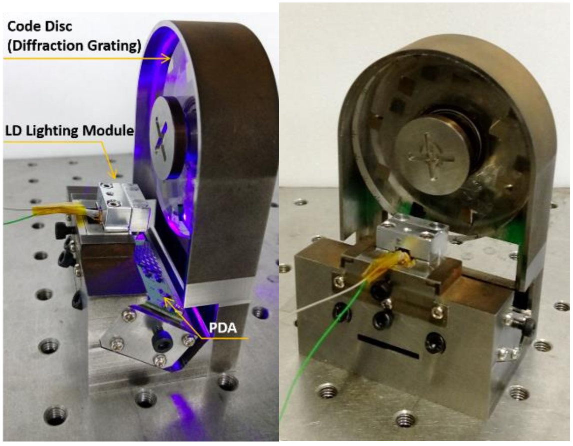


Fig. 7 Optical code disc, LD lighting module, and PDA placed in the positioning mechanism

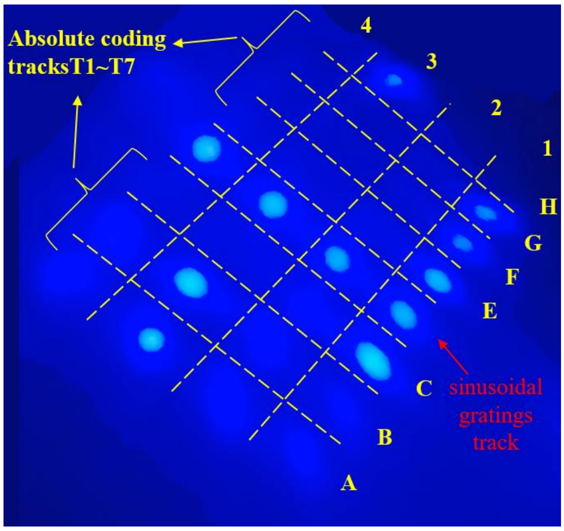


Fig. 8(a) Actual light spot position obtained when the code disc rotates nearly 180 degrees (corresponding code NO.8202)

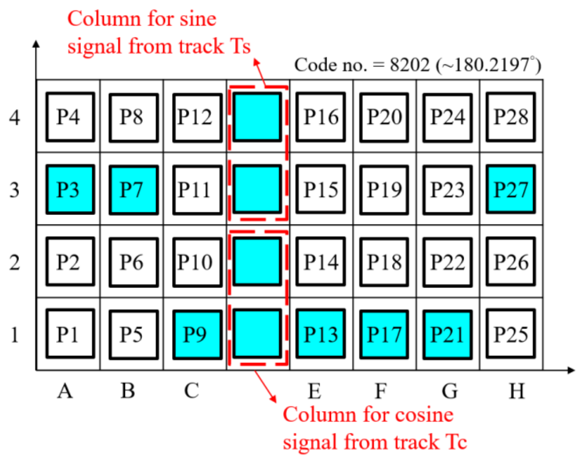


Fig. 8(b) Code NO.8202 (rotation angle = 8202 × 360/ 2^{14} = 180.2197 degrees)

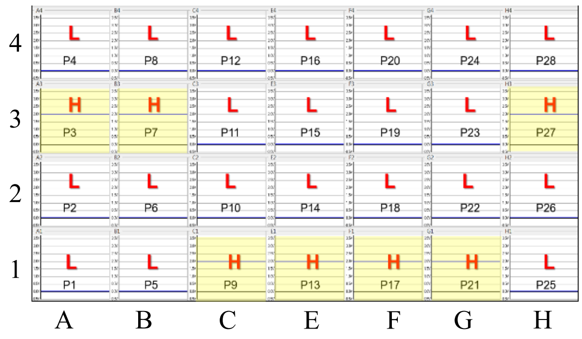


Fig. 8(c) 7×4 PDA through ADC (Advantech PCI-1715U: 500 kS/s, 12-bit, 32-ch) voltage signal after sampling. H is the signal of the light source that is detected by the PD (approximately 2 V); L is the signal of the light source that is not detected by the PD (approximately 0 V).

CONCLUSIONS

ZEMAX can be used to quantitatively characterize the optical properties of diffractive opto-electronic encoders. Through the assistance of simulation software, this study designed grating stripes with different periods and orientations for encoding. Those stripes then underwent the verification of photoelectric conversion signal. The experimental results confirm that diffraction-based optical methods can achieve angle measurment with a 14 bit/rev. resolution, which is in line with the design. Future research can use this encoding architecture as a basis and, by way of binary sinusoidal gratings, design Ts and Tc tracks and their corresponding PDA. A staggered periodic arrangement of two tracks in the radial positions can enable the PDA to detect changes in the energy of two reflection orders with a phase difference and, through signal interpolation technology, to upgrade a 10–12 bit/rev signal resolution.

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超高解析度繞射式光學編碼器設計與製作

陳易呈 沈聖智
國立成功大學系統及船舶機電工程學系
陳易呈
工業技術研究院/智慧微系統科技中心/智慧感測機電整合技術部

摘要

旋轉編碼器是工業應用中做為角度測量的重要裝置，超高精度的角度量測技術是伺服運動定位的基礎，決定著半導體加工、超精密加工，甚至是精密對位組裝的能力。本研究以光學讀取頭架構為原型，利用雷射光源入射光柵(Grating)狹窄結構時所產生的繞射現象開發一高精度的絕對型光學編碼器(Absolute Optical Encoder)，解決幾何光學

設計方式下因編碼盤(Code Disc)縮小造成雜訊比(Signal to noise ratio, SNR)降低的問題。實驗結果顯示，本研究提出之繞射式光學編碼器架構可達14 bit/rev.之解析度，若再加入二維弦波光柵設計，即可透過訊號細分割技術，再提升 10~12 bit/rev.之訊號解析度，達到超高精度量測的目標。