Introduction of SPPE-1000
Scanning Interference Optical Encoder

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Abstract

This white paper discusses a new position encoder product (SPPE-1000), which integrates SPPE (scanning probe position encoder) technology developed by NanoWave Inc. and modulated laser interference encoder optics developed by Nikon Corporation. High frequency scan of laser beam on a moving scale creates harmonic signals which contain position information. Low-latency phase detection logic using PLL (Phase-Locked Loop) decodes the position information down to 7.6pm LSB from 4 micrometer pitch grating scale, all with spectrum noise density better than. The entire signal processing logic is compact enough to be implemented within a single low-cost FPGA chip, which also keeps the cost of the system low. Its relatively long grating pitch simplifies the installation process significantly and results in great robustness in attaining the specified accuracy.

1. Introduction

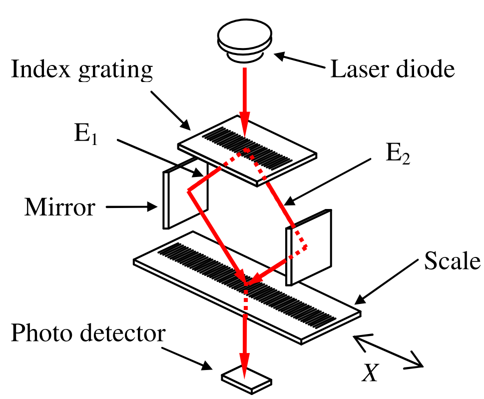

Fig.1 Conventinal interference optical encoder

Industries in nanotechnology, mass data storage, semiconductor equipment require highly-reliable machines with extremely fast and stable positioning capability at sub-nanometer level. Today, laser interferometers, capacitance gauges and interference laser encoders such as the one illustrated in Figure 1 has achieved sub-nanometer resolution; however, each comes with their own issues. Laser interferometer operated in air is sensitive to minute changes in air temperature, humidity and atmospheric pressure, which hinders repeatable measurement. Capacitance gauge is often limited by its short measurement range and difficult alignment process during the initial set-up.

As a result, the demand for position encoders has been increasing despite the fact that a high-end position encoder often requires meticulous installation and signal adjustment procedure due to the extremely small pitch grating (~0.5 micron) and short working distance employed in its basic design. Furthermore, conventional position encoder may produce unacceptable interpolation errors without proper signal adjustments (e.g. exact amplitude matching, DC offset cancellation of two sinusoidal output signals, etc.)

2. Concept of Scanning Interference Optical Encoder

2.1 Scanning Encoder Optics

Figure 2 illustrates the configuration of the new scanning encoder which integrates an optical scanning mirror and conventional interference encoder optics using a transmission type scale. The reflection type scale can be also used with similar optical set-up.

Coherent laser beam is angularly modulated by the scanning mirror and enters through the index grating, which divides the beam into +1/-1 order diffracted lights (E_1, E_2). Each diffracted light is reflected by the mirror and then recombined at the surface of the moving scale, which forms the interference image on the photo detector. The moving scale employs the same pitch as the one used in the index grating.

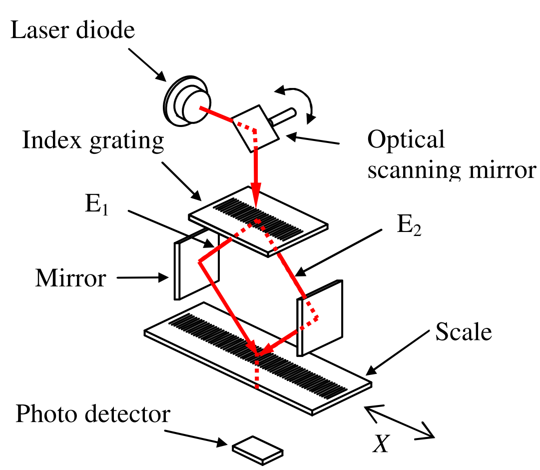

Fig.2 Scanning interferance optical encoder

The +1/-1 order laser beams on the surface of the moving scale can be modeled as Equation (1) and (2) respectively with the complex amplitude expression.

$$E_1 = A_1 \exp(jkL_1 + \frac{2\pi X}{P}) \tag{1}$$

$$E_2 = A_2 \exp(jkL_2 - \frac{2\pi X}{P}) \tag{2}$$

, where A_1, A_2 are amplitudes of the light intensity and L_1, L_2 are nominal optical path lengths respectively. P is the pitch of the moving scale and the index grating. X is the relative position between the index grating and the moving scale. Assuming that the incident angle and thus the diffraction angle of the light entering into the index grating is modulated in a single frequency sinusoidal waveform, the complex amplitude of +1/-1 order diffracted lights can be described as;

$$E_1 = A_1 \exp\{\ jk(L_1 + M\sin\omega t) + \frac{2\pi X}{P}\ \} \tag{3}$$

$$E_2 = A_2 \exp\{\ jk(L_2 - M\sin\omega t) - \frac{2\pi X}{P}\ \} \tag{4}$$

, where M is the amplitude of the modulation, and ω is the angular frequency.

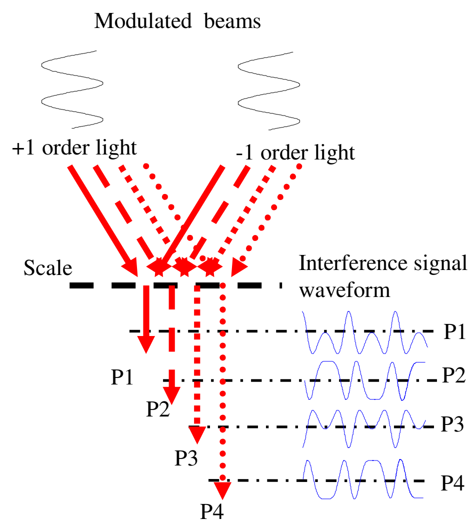

Fig.3 Scanning interference signal waveform as a function of the relative position between the head and the scale

Assuming that $L_1 \approx L_2$, interference intensity distribution I_1 is then calculated as:

$$I_1 = |E_1 + E_2|^2 \approx A_1{}^2 + A_2{}^2 + 2A_1A_2\cos(\frac{4\pi X}{P} + 2M\sin\omega t) \tag{5}$$

Figure 3 illustrates that the interference intensity waveform, I_1 , changes as the relative position between the index grating and scale changes from X=P1,P2 to P4.

2.2 SPPE Decoding Logic

Equation (5) shows that I_1 is now a phase modulated signal, which is a function of time. The Fourier expansion analysis of Equation (7) in time domain shows:

$$
\begin{aligned}
I_1(t) &= A_1^2 + A_2^2 + 2A_1A_2J_0(2M)\cos(\frac{4\pi X}{P}) \\
&- 4A_1A_2\sin(\frac{4\pi X}{P})\sum_{m=1}^{\infty} J_{2m-1}(2M)\sin\{(2m-1)\omega t\} \\
&+ 4A_1A_2\cos(\frac{4\pi X}{P})\sum_{m=1}^{\infty} J_{2m}(2M)\cos\{2m\,\omega t\}
\end{aligned} \tag{6}
$$

where the function $J_n(2M)$ represents Bessel's Function of the first kind.

This result reveals that quadrature information of position $\sin(\frac{4\pi X}{P})$ and $\cos(\frac{4\pi X}{P})$ is expressed as amplitude of the high-order harmonics of the scanning mirror modulation frequency. Therefore once these terms, $\sin(\frac{4\pi X}{P})$ and $\cos(\frac{4\pi X}{P})$ are obtained, the position encoder can be realized.

Although there can be many methods to decode the position information from the signal described in Equation (6), reference [3] shows a phase detection method using an all-digital PLL (Phase-Locked Loop). Figure 4 shows a schematic block diagram of the detection logic (SPPE: Scanning Probe Position Encoder) developed by NanoWave, Inc. In this case, the incoming signal is first multiplied by $\cos(0.5\omega t)$ converting the position information into a phase information and then use $\sin(2.5\omega t)$ as a reference frequency for the following PLL in order for extracting the position information, X in Equation (6). Since the motion of the target object is usually smooth over short periods of time, the noise spectrum outside of the fringe oscillation harmonics are effectively eliminated by a phase-synchronous detection technique, while the measurement range can be well beyond the scale period.

Unlike the conventional position encoder, SPPE technology uses only single signal information for the position measurement. Thus, the measurement result inherently shows low interpolation error even without any calibration processes. The active scanning beam over the scale surface also provides real-time information such as signal amplitude and DC offset and can be adjusted or cancelled in real-time.

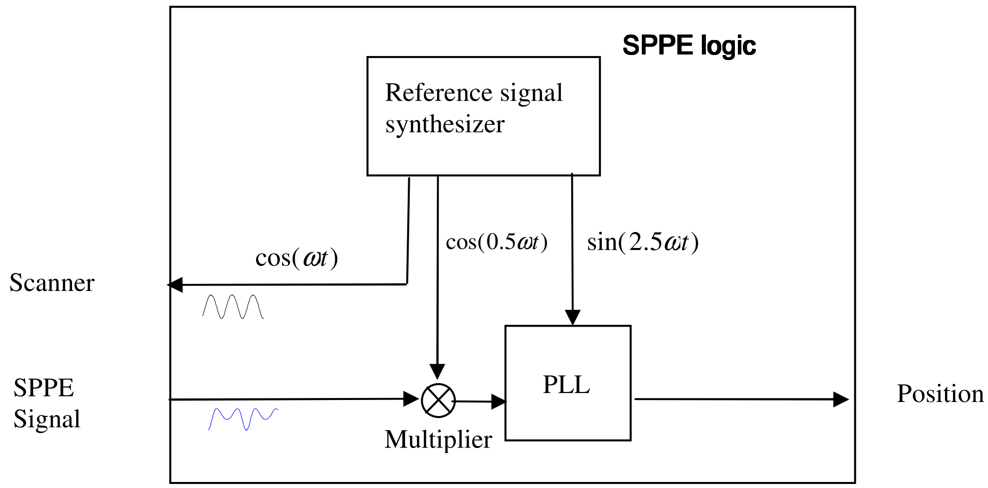

Fig.4 Position decode logic

3. SPPE-1000 Production Model

3.1 Optical Head

Figure 5 illustrates the optical configuration of the encoder head used in the actual product model. Instead of using a transmission type scale described in Figure 2, the SPPE-1000 is designed to use a reflection type scale for ease of installation and space saving purposes. In order to avoid heat transmission from the laser diode, laser light is guided through a single mode optical fiber. Laser beam incident from the fiber edge is modulated by a tiny optical scanner and then collimated. The optical scanner is made from quartz crystal which has torsional mechanical resonance of around 200 kHz. The index grating consists of 4μm pitch grating.

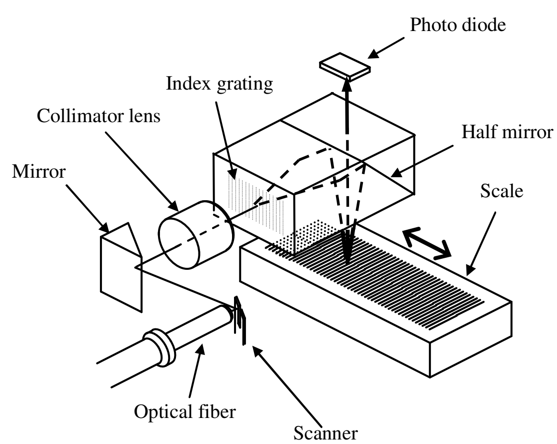

Fig.5 Scanning interference encoder optics

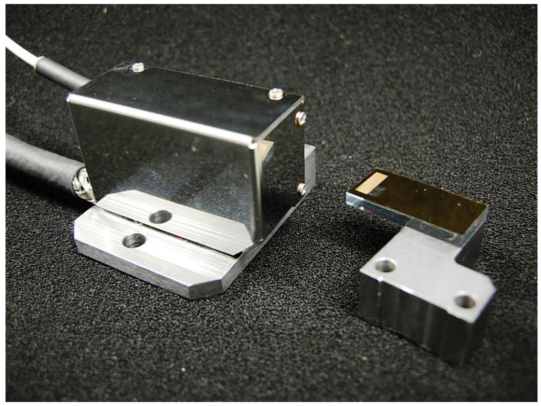

Fig.6 Scan encoder ptototype head

Figure 6 is a photo of the actual optical head. The head unit is packaged roughly within 40mm x 17mm x26mm dimension without the base mount. The length of the measurement is dependent on the scale length. NanoWave can supply up to 1 meter as requested by customers.

3.2 System Configuration

Figure 7 illustrates the system configuration of a scanning encoder. A ~200 kHz reference frequency signal is generated by the synthesizer inside the FPGA board and sent to the scanner through DAC, which drives the optical scanner. The FPGA logic continuously adjusts the reference frequency so that the scanner is always driven at near its peak resonant frequency. This way, the input energy to the head is minimized while the phase noise associated with the position detection stays low. All logic is implemented in a compact and low cost FPGA package.

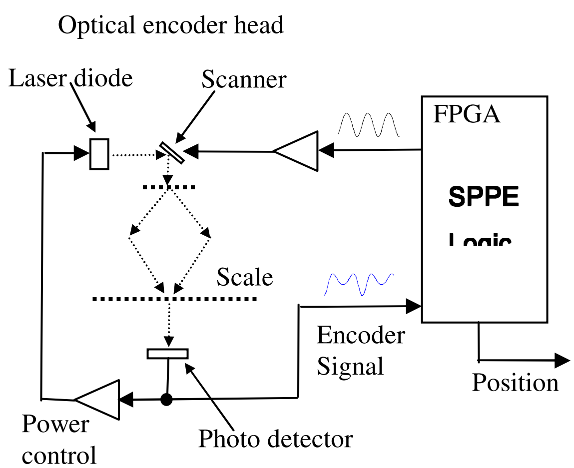

Fig.7 System configuration

Figure 8 shows the position information detected through the SPPE logic. The position data LSB 7.6pm and noise RMS $1pm/\sqrt{Hz}$ has been achieved.

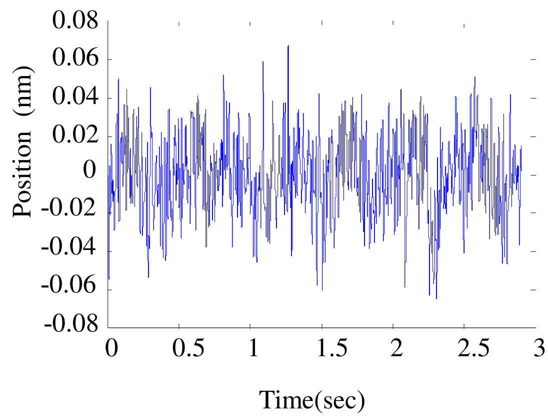

Fig.8 Position data

4. Long Term Stability and Set-up Tolerance

Figure 9 shows the result of the long term stability test. The optical head and the scale are fixed within the stainless steel block. Then, its position output is recorded for one month. The total drift of the position output is within 10 nm, which is comparable with high-end conventional encoders.

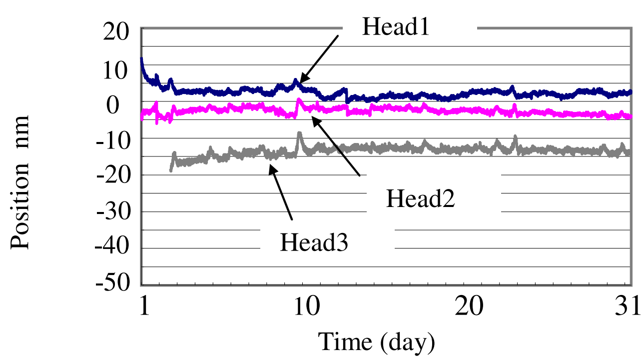

Fig.9 Long term stability

Figure10 shows the angular error tolerance data. Large grating pitch (4μm) of this scanning encoder allows over 1.5’ (0.4 mrad) tolerance.

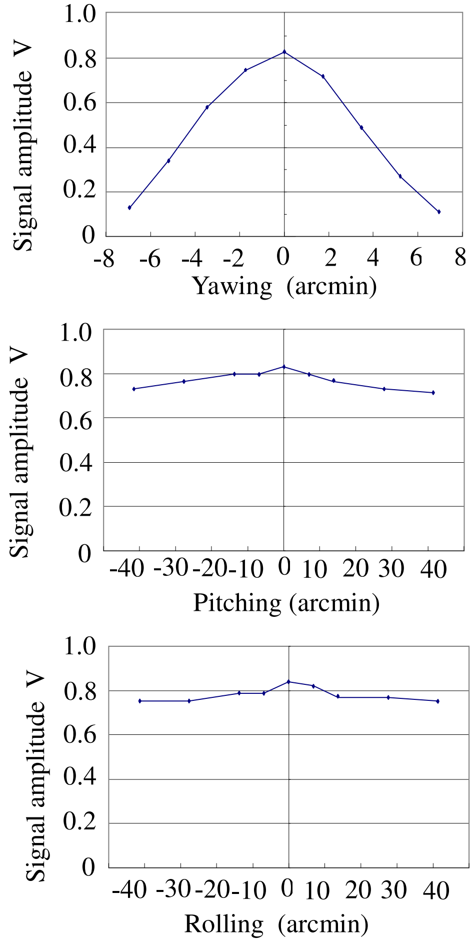

Fig.10 Mounting angle tolerance

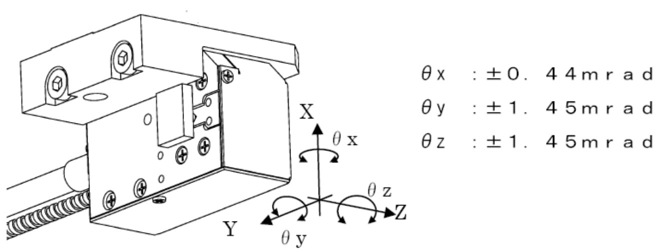

Figure 11 Definition of encoder head axis and rotational tolerance

5. Conclusion

A new position encoder product (SPPE-1000), which integrates SPPE (scanning probe position encoder) technology developed by NanoWave Inc. and modulated laser interference encoder optics developed by Nikon Corporation was presented.

Due to its excellent interpolation accuracy and robustness, the product design allows the use of 4 micron pitch grating while achieving noise spectrum density of $1pm/\sqrt{Hz}$ RMS with 7.6pm LSB resolution. As shown in Table 1 below, its relatively long grating pitch significantly simplifies the installation process and results in great robustness and tolerance in attaining the specified accuracy.
Furthermore, its carefully designed optical system and measurement technology inside the SPPE-1000 head proved to be highly stable for long term measurement, achieving only a few nanometer fluctuations over a 1 month period test.

Table 1 SPPE-1000 Specifications

Item	Specification
Size	40 x 40 x 20mm
Gap	2.4±0.1mm
Grating pitch	4μm
Measuring length	2mm (up to 1m)
Resolution	7.6pm
Max speed	400mm/s
Linearity	<10nm
Repeatability	<10nm
Reference mark repeatability	<10nm
Mounting tolerance	
	θx ±0.44mrad (±1.5’)
	θy ±1.45mrad (±5’)
	θz ±1.45mrad (±5’)

Finally, FPGA optimized code allows low-latency phase detection using PLL (Phase-Locked Loop), which also keeps the overall system cost low. Due to the portability of the SPPE-1000 FPGA core, end-users can also develop their own high-performance motion control system under NanoWave licensing program.

References

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[3] T.Ohara: Scanning Probe Position Encoder (SPPE)-a new approach for high precision and high speed position measurement system, SPIE 26th Annual International Symposium on Microlithography Proceedings