Compact Nanometer Resolution Fiber-optic Encoder with Embedded Reference Mark

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Abstract

High-precision industries require position sensors with challenging requirements for resolution, size, EMI-immunity, thermal noise, and other performance factors. We have developed a nanometer-resolution encoder to address such requirements. The readhead consists of a grating mask covering a fiber bundle mounted in a ferrule, with a diameter less than 3 mm. The monolithic design allows vacuum compatibility. The electronics-free approach gives low thermal noise and EM immunity. Optical fibers allow long cable lengths (100+ m possible) at high bandwidth. We present a new type of reference (REF) mark that can be embedded in the 4µm-period incremental (INC) scale. The readhead can sense both INC position and REF signal simultaneously. Under specified operation tolerances, REF signal repeatability is less than 0.5 µm, well within the INC signal period of 2 µm as required for unambiguous performance.

1 Principle of operation

Figure 1 shows the basic principle of operation. A fiber bundle has 6 multimode fiber receivers wrapped around a single mode fiber that provides light to the scale. The scale phase grating eliminates 0th order diffraction, so that only ±1 orders interfere at the mask grating to provide a sinusoidal INC signal with scale motion. The four INC receivers have mask gratings shifted in phase by 90° increments to allow generation of analog quadrature signals. The INC portion of the system is described more fully elsewhere [1-3].

The four-receiver configuration leaves two fiber receivers free for embedded REF mark detection. This configuration allows a single-readhead, embedded-mark solution for an INC+REF system that allows manufacturing efficiency and good mechanical registration [4]. A mark of width w is embedded into the INC scale, and receivers R1 and R2 detect 0th order light reflected from the mark through mask slits that are slightly offset in x. The arrangement produces REF signals R1 and R2 that are offset from each other in scale position. With thresholding, their sum produces a digital valid signal when the readhead is near the mark, and their difference produces a zero-crossing signal. A valid zero-crossing (the digital Z signal) indicates presence of the mark directly under the readhead.

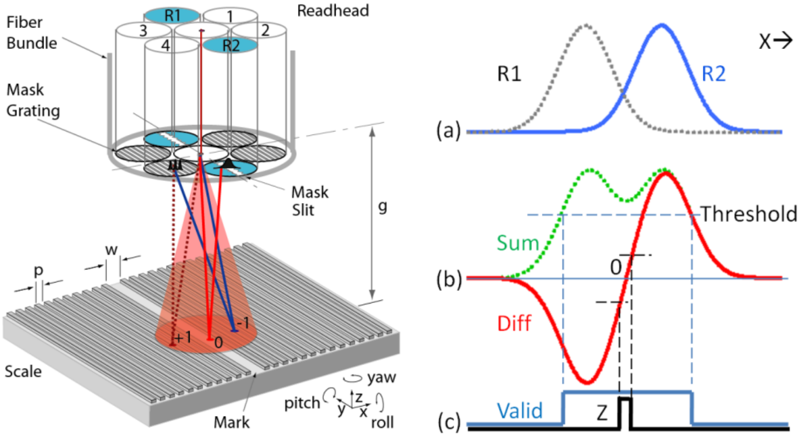

Figure 1: Embedded REF mark, optical concept (left) and signal processing (right). Rays +1 and -1 create the INC signal on Receiver 4, and Ray 0 creates the REF signal on Receiver R2. The sum and difference of R1 and R2 with thresholding produce digital valid and REF Z signals.

2 Reference Mark Designs and Simulation

Design contstraints for embedded reference marks hinge primarily on requirements to reuse the basic INC scale fabrication method, to produce a robust, repeatable REF signal, and to disrupt INC signals as little as possible. Previous approaches such as Fresnel zone-plate marks [5] we found too disruptive when embedded. We developed two types of embedded REF marks, examples of which are shown in Figure 2(a): a narrow mirror mark and a wider zone duty-cycle (ZDC) mark [4]. The mirror mark is narrow so as not to disrupt the main scale but gives a broad, unfocused REF signal (which can lower sensitivity and, ultimately, repeatability). The ZDC mark is subtly embedded into slight variations in the duty cycle of the scale grating. It preserves INC signal phase, maintains INC grating structure continuously throughout the mark to reduce disruption, and provides phase reversal according to Fresnel zone spacing. Thus, by choosing mark width and amount of duty cycle variation, we can tailor both focused-spot width and strength to achieve repeatable REF signals while minimizing disruption of INC signals. Figure 2(b) shows a comparison of the signals from mirror and ZDC marks. The simulation and experiments used the same approach and design as in [1], with the addition of embedded marks in the scale. To improve experimental results, we developed special serrated REF mask slits [4] in order to filter out high spatial frequency signal oscillations from relatively small contributions of ±1 diffractive orders, as Figure 2(c) shows.

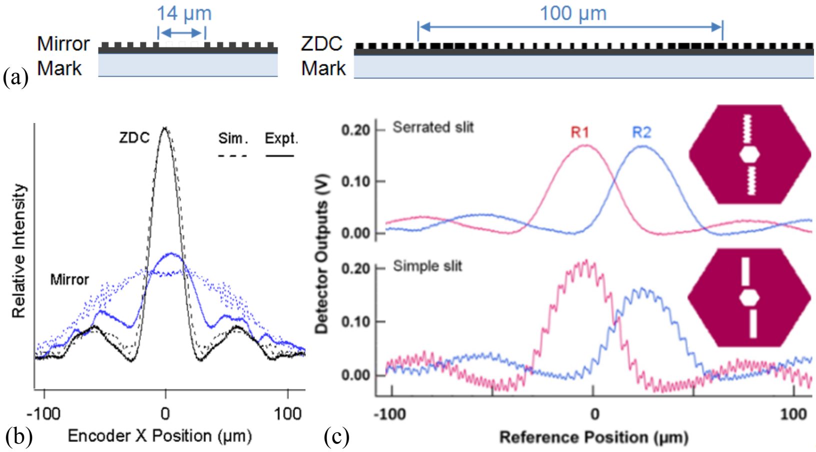

Figure 2: (a) Mark types (b) resulting REF signals (c) effect of mask REF slit shape.

3 Experimental results

Our encoder and experimental setup for INC signal characterization (error plots and signal levels with misalignment) is described elsewhere [1]. We use the same setup for reference mark testing, where we collect reference signals R1 and R2 and process them offline to create the zero crossing signal. For reference marks of both types and various widths, we measure INC signal errors (single pass) and reference mark repeatability (20 passes). Figure 3 shows REF repeatability and INC error plot for a ZDC mark with readhead at best alignment. We tested over typical misalignment tolerances (gap 5±0.1 mm, pitch 0±1°, roll 0±1°, yaw = 0±0.1°) and found worst case repeatability and INC error to be 2X and 3X larger respectively than at best alignment, still well within requirements. Similarly, we tested the mirror mark type and found it to meet basic requirements.

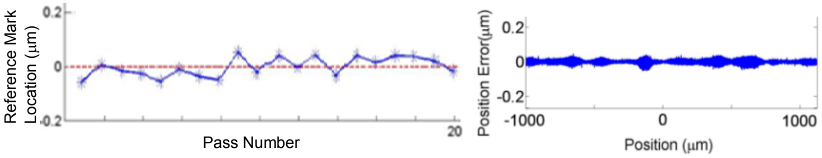

Figure 3: Performance of the ZDC mark. Left: measured location of zero-crossing relative to position from INC signal. Repeatability for 20 passes is 0.036 μm (1σ) Right: INC position error (long range error removed) when traveling over a reference mark located at position x=0. The error is 0.08 μm (peak to peak).

4 Conclusion

The optical fiber based encoder offers a compact, high resolution readhead with large misalignment tolerances and unique performance characteristics such as EM immunity, low thermal noise and long cable lengths. Reference capability can be embedded into the INC system with appropriate scale, readhead mask, and processing. Both mirror and ZDC embedded reference marks meet basic requirements to repeatably and unambiguously point to a specific INC signal period within operating tolerances, with better performance from the ZDC mark. Both mark types are options for providing a reference signal in a future product.

References:

[1] Tobiason JD, Zwilling AM, Emtman CE, Takahashi T, Kawada H, Compact, nanometer-resolution, fiber-optic encoder. ASPE Proceedings, Vol. 2844, Oct 2009.

[2] Tobiason JD, US patents 6906315, Nov 15, 2002; 7126696, Sep 30, 2003.

[3] Takahashi T, European patent EP 1972902A1, Mar 18, 2008.

[4] Tobiason JD, US patents 2009/0027692A1, Jan 29, 2009; 2009/0135435A1, May 28, 2009; patent applied for (private communication).

[5] Sussman M, Elementary diffraction theory of zone plates, Am. J. Phys. 28, 394 (1960)