Optical design for laser Doppler angular encoder with subnanoradian sensitivity

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Introduction

Recently, with the availability of third-generation synchrotron radiation facilities, such as the Advanced Photon Source, and the development of high-energy-resolution x-ray optics, x-ray scattering experiments with 10 keV or higher energies and sub-meV resolution has become practical [1]. In these experiments, ideally, the motion control on the monochromating crystals has to be at the 1–10 nanoradian level or better. However, if closed-loop feedback devices will be used, the required resolution for the motion sensor (angular encoder) must be at the subnanoradian level over a measuring range of eight degrees. There is, at present, no commercially available angular encoder with subnanoradian resolution over an eight-degree measuring range. In the field of grating-based encoders, one of the best available products is ROD-800 from Heidenhain, which has 175 nanoradian resolution with 360 degree measuring range when coupled with AWE 1024 interpolator [2]. As for commercial laser interferometers, the Hewlett Packard HP-5527B [3] and Zygo ZMI-1000 [4] provide a 20–100 nanoradian angular resolution from a few degrees up to 20 degrees angular measuring range. Although some tilt-sensors (e.g., the Applied Geomechanics Model-520) have 10 nanoradian resolution, they only cover a measuring range of less than 0.01 degree with a very long measurement setting time (0.1–30 seconds). In a laboratory setup based on a polarization-encoded Michelson interferometer system, a few nanoradian resolution has been achieved with a setup size about 610 mm x 1220 mm [5]. The overall dimension of the encoder system is critical to the performance of the closed-loop feedback system. In our case, however, the large setup size would cause complications for the system's thermal and mechanical stability. This report presents a novel laser angular encoder system, which is based on a laser Doppler displacement meter and self-aligning three-dimensional (3-D) multiple-reflection optics [6]. With this new angular encoder, subnanoradian resolution has been attained in an eight degree measuring range in a compact setup.

Methods and Materials

<u>Optical design</u>

A typical sine-bar configuration was used in this design to convert the angular measurement to a linear displacement measurement. The length of the sine bar was restricted to less than 310 mm by the monochromator structure and system stability limits. To achieve subnanoradian angular resolution, the resolution needed for the linear displacement measurement had to be in the near-angstrom range. The laser Doppler displacement meter (LDDM) is based on the principles of radar, the Doppler effect, and optical heterodyning [7]. We chose a LDDM as our basic system not only because of its high resolution (10 nm typical) and high measuring speed but also because of its unique performance independent of polarization, which provides the convenience to create a novel multiple-reflection-based optical design to attain near-angstrom linear resolution extension [8].

Figure 1 shows the self-aligning 3-D multiple-reflection optical design for the LDDM system resolution extension. In this design, the heterodyning detector is housed coaxially inside the frequency-stabilized laser source. Instead of a typical single reflection on the moving target, the laser beam is reflecting 24 times between the fixed base and the moving target. The laser beam, which is reflected back to the heterodyning detector, is frequency shifted by the movement of the moving target relative to the fixed base. With same LDDM laser source and detector electronics, this optical path provides 12 times the resolution extension power for the linear displacement measurement and encoding.

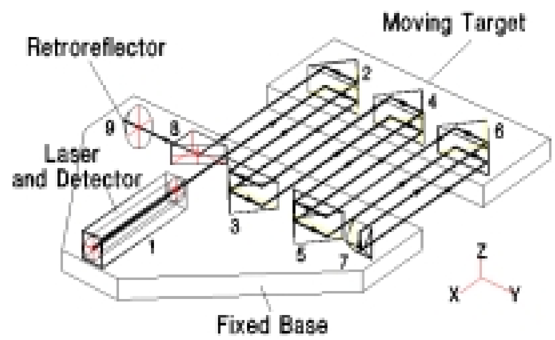

Figure 1: Configuration of a self-aligning 24-reflection optical design. In this figure, item 1 is the frequency-stabilized laser source with heterodyning detector, items 2 – 8 are right-angle prisms, and item 9 is the end retroreflector.

As shown in Fig. 1, the laser beam is reflected by a set of right-angle prisms 2, 3 ,4, 5, and 6. The retroreflector 7 reflects the beam back to a different zoom on prisms 6, 5, 4, 3, and 2. Prism 8 delivers the beam to the end retroreflector 9. Then, the laser beam is reflected back to the laser head, following the original path and finally reaching the detector, which is arranged coaxially in the laser-head housing. The use of prism 8 and end retroreflector 9 together provides for a very practical self-alignment capability. This reduces the total system assembly and alignment time substantially. Because the laser beam is reflected in the same optical path twice with opposite directions, this multiple-reflection optical design provides unique system stability performance. The 3-D optical path configuration results in a compact and integrated optical design that optimizes the system's anti-vibration performance, which is critical for subnanoradian resolution in measurements. There are many ways to change the total amount of the reflection times in this design. For instance, to expand the optical path in the Y direction, one can add more prisms between elements 2 to 6, or expand the optical path in the Z direction by adding one or more additional sets of prisms. The limit of the maximum reflection times is determined by the optical reflectivity of the reflecting element to be used and the sensitivity of the LDDM laser detector electronics. Special coatings could be used on the surfaces of the reflecting elements to optimize the results. To apply the above multiple-reflection design for a laser Doppler angular encoder (LDAE), the moving target is mounted on the end of a sine bar to measure the shaft-rotation angular displacement. To extend the angular measuring range, prisms with different sizes are used for prisms 2, 3, 4, 5, and 6 in Figure 1.

Results

<u>Application on x-ray monochromator</u>

A prototype LDAE has been developed for high-energy-resolution x-ray scattering applications at the Advanced Photon Source undulator beamline 3-ID [9]. We have modified the monochromator (AAG-100 [10], manufactured by Kohzu Seiki Co. Japan) sine bar and related structure for the LDAE assembly. Figure 2 is the plot of the test results that correlates the performance of our LDAE with a Heidenhain ROD-800 optical encoder with a 2 arc-sec accuracy and 175 nanoradian resolution. The slope of the correlation data in Fig. 2 shows that our LDAE has a 0.27632 nanoradian per count readout sensitivity. A 100 mrad/sec rotation speed was tested for a laboratory setup in the eight degree measuring range without any encoder miscounting.

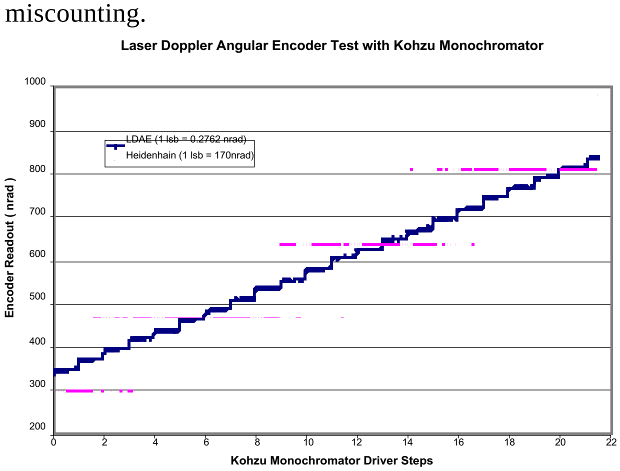

Figure 2: Plot of the test results that correlates the performance of LDAE with a Heidenhain ROD-800 optical encoder with 175 nanoradian resolution.

It is very difficult to prove a subnanoradian system resolution experimentally in an open-loop system because of the thermal and mechanical vibration noises. However, with a commercial PZT driver, such as a Queensgate NPS3330, we have made an open-loop test with two 6.6 nanoradian motion steps. During this test, the same sine bar and LDAE moving target were driven by a Queensgate PZT driver. Figure 3 is the plot of the test results that correlates the readout sensitivity with Queensgate PZT driver two 6.6-nanoradian jumps. The error bar reflects the PZT driver system noise, which was about 1.9 nanoradian peak-to-peak.

Conclusions

We have developed a LDAE. Twenty-four multiple reflections were achieved without alignment difficulty. With a customized laser Doppler displacement meter and a 330 mm sine-bar structure, this novel angular encoder has a sub-nanoradian sensitivity in an eight degree measuring range. Its compact setup [about 60 mm (H) x 150 mm (W) x 370 mm (L) in size] optimizes the system's antivibration performance. Preliminary studies for closed-loop feedback control with this LDAE system are in progress.

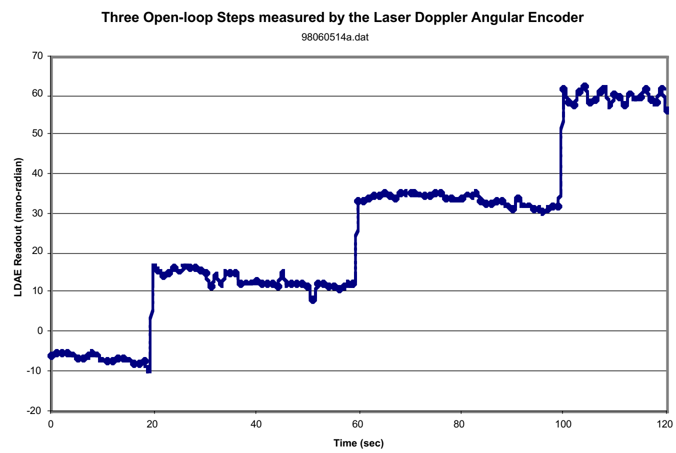

Figure 3: LDAE measurement of 25 nanoradian steps driven by the monochromator stepping motor.

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References

[1] T.T. Toellner *et al*., *Appl. Phys. Lett.* **71** (15), 2112–2114 (1997).
[2] Heidenhain GmbH, ROD 800 catalogue, str. 5, D-83301 Traunreut, Deutschland (1996).
[3] Hewlett-Packard Co., HP-5527B catalogue, s. Manhatttan Av. Fullerton, CA 92631, USA (1996).
[4] Zygo Co., ZMI-1000 catalogue, Laurel Brook Road, Middlefield, CN 06455, USA (1996).
[5] E.G. Kessler *et al*., *NIST report*, revised (1993).
[6] D. Shu, U.S. Patent granted No. 5,896,200, (1999).
[7] C. Wang *et al*., *Laser & Optronics* **Sept**., 69 (1987).
[8] D. Shu, E. E. Alp, J. Barraza, and T. M. Kuzay, *Proceedings of SPIE*, **3429**, 284-292 (1998).
[9] D. Shu, E. E. Alp, J. Barraza, T. M. Kuzay, and T. Mooney, *Journal of Synchrotron Radiation* **5**, 826–828 (1998).
[10] Kohzu Seiki Co., Ltd., catalogue, 2-27-37 Mishuku,

Setagaya-ku, Tokyo 154, Japan (1996).