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Optical design for laser Doppler angular encoder with sub-nrad sensitivity

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A novel laser angular-encoder system has been developed based on the principles of radar, the Doppler effect, optical heterodyning and self-aligning multiple-reflection optics. Using this novel three-dimensional multiple-reflection optical path, an increase in resolution of 10 to 20 times has been reached compared with commercially available laser Doppler displacement meters or laser interferometer systems. With the new angular encoder, sub-nrad resolution has been attained in the 8° measuring range in a compact set-up [about 60 (H) × 150 (W) × 370 mm (L)] for high-energy-resolution applications at the Advanced Photon Source undulator beamline 3-ID.

Keywords: angular encoders; nrad sensitivity; optical design.

1. 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 down to sub-meV resolution have become practical (Toellner *et al.*, 1997). In these experiments, ideally, the motion control on the monochromating crystals has to be at the 1–10 nrad level or better. However, if closed-loop feedback devices are used, the resolution required for the motion sensor (angular encoder) will be at the sub-nrad level over a measuring range of 8°.

There is, at present, no commercially available angular encoder with sub-nrad resolution over an 8° measuring range. In the field of grating-based encoders, one of the best available products is ROD-800 from Heidenhain GmbH (Traunreut, Germany), which has 175 nrad resolution with a 360° measuring range when coupled with an AWE 1024 interpolator. As for commercial laser interferometers, the Hewlett Packard HP-5527B (Hewlett Packard, Fullerton, CA, USA) and Zygo ZMI-1000 (Zygo, Middlefield, CN, USA) provide a 20–100 nrad angular resolution from a few degrees up to 20° angular measuring range. Although some tilt sensors, such as the Applied Geomechanics Model-520, have 10 nrad resolution, they only cover a measuring range of less than 0.01° with a very long measurement-setting time (0.1–30 s).

In a laboratory set-up based on a polarization-encoded Michelson interferometer system, a few nrad resolution has been achieved with a set-up size of about 610 × 1220 mm (Kessler, 1992). The overall dimension of the encoder system is critical to the performance of the closed-loop feedback system. In our case, however, a large set-up size will cause complications for the system's thermal and mechanical stability.

This paper presents a novel laser angular-encoder system, which is based on a laser Doppler displacement meter (LDDM) and self-aligning three-dimensional multiple-reflection optics (Shu, 1997). With this new angular encoder, sub-nrad resolution has been attained in an 8° measuring range in a compact set-up [about 60 (H) × 150 (W) × 370 mm (L)].

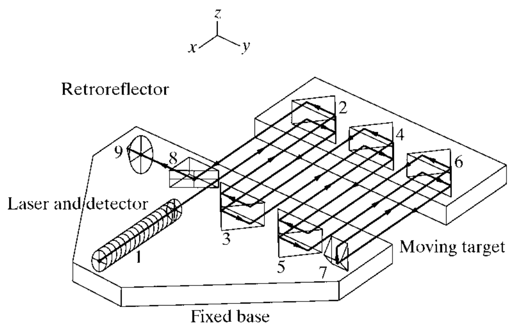

Figure 1
Configuration of the self-aligning 24-reflection optical path. In this figure, item 1 is the frequency-stabilized laser source with heterodyning detector, items 2–8 are right-angle prisms, and item 9 is the end retroreflector.

2. Optical design

A typical sine-bar configuration was used in this design to convert the angular measurement to a linear displacement measurement. The dimension of the sine bar was restricted to less than 310 mm in length by the monochromator structure and system stability limits. To achieve sub-nrad angular resolution, the resolution needed for the linear displacement measurement has to be in the near-ångstrom range.

The LDDM is based on the principles of radar, the Doppler effect and optical heterodyning (Wang, 1987). We have chosen an LDDM as our basic system not only because of its high resolution (10 nm typically) and high measuring speed but also because of its unique performance independent of polarization; this allows us to create a novel multiple-reflection-based optical design to attain near-ångstrom linear resolution extension.

Fig. 1 shows the self-aligning three-dimensional 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 reflects 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 the same LDDM laser source and detector electronics, this optical path provides 12 times the resolution extension power for the linear displacement measurement and encoding.

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 reaches 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 in opposite directions, this multiple-reflection optical design provides unique system stability performance. The

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three-dimensional optical-path configuration results in a compact and integrated optical design that optimizes the system's anti-vibration performance, which is critical for sub-nrad 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; to expand the optical path in the z direction one can add another one or more sets of prisms. The limit of the maximum reflection times is determined by the optical reflectivity of the reflecting element 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 to 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 Fig. 1.

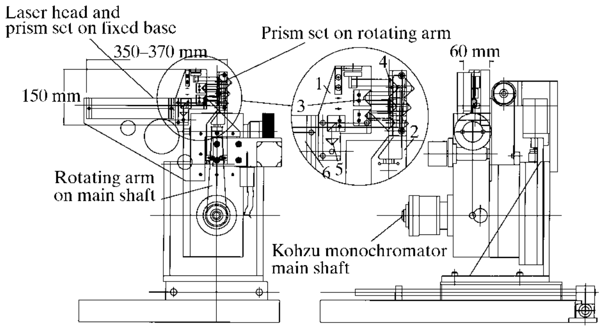

Figure 2
Configuration of the LDAE system with 24 reflections on the high-energy-resolution crystal monochromator. In this figure, item 1 is the fixed base attached to the monochromator base; 2 is the moving sine-bar arm attached to the monochromator rotary shaft; 3 is the set of right-angle reflective prisms on the fixed base; 4 is the set of prisms on the moving arm; 5 is the axial retroreflector set on the fixed base; 6 is a custom-made commercial laser Doppler displacement meter with a heterodyne detector inside.

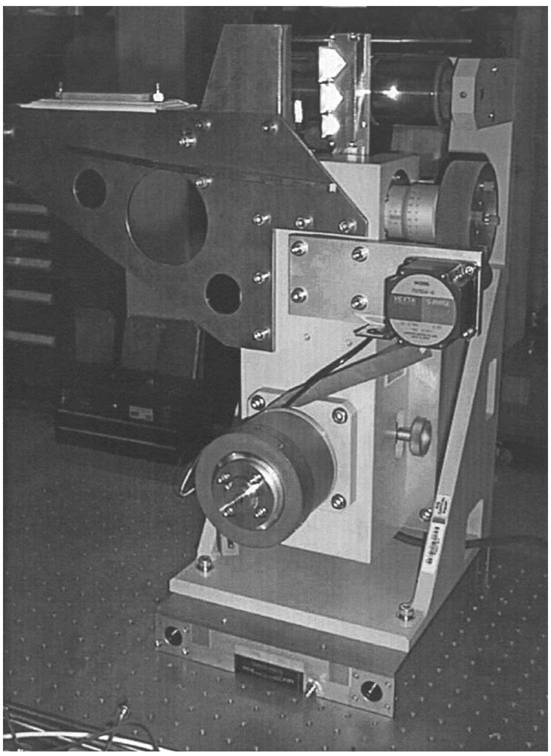

Figure 3
A photograph of the monochromator together with the mounted LDAE.

3. Application to an X-ray monochromator

A prototype LDAE has been developed for high-energy-resolution X-ray scattering applications at the Advanced Photon Source undulator beamline 3-ID. We have modified the monochromator (AAG-100, manufactured by Kohzu Seiki Co., Tokyo, Japan), sine bar and related structure for the LDAE assembly. Fig. 2 shows the configuration of an actual LDAE system with 24 multiple reflections on one end of the sine bar which rotates the shaft on which the asymmetrically cut crystals are mounted. The overall dimensions of the LDAE are also indicated in the figure. In the enlarged central part, the LDAE system components can be identified as follows: 1 is the fixed base attached to the monochromator base; 2 is the moving sine-bar arm attached to the monochromator rotary shaft; 3 is the set of right-angle reflective prisms on the fixed base; 4 is the set of prisms on the moving arm; 5 is the axial retro-reflector set on the fixed base; and 6 is a custom-made commercial LDDM with a heterodyne detector inside (Optodyne Inc., Compton, CA, USA). The frequency-stabilized laser beam from the laser head passes through prism sets 3, 4 and 5, then back to the detector. To control the system thermal stability, a water-cooling jacket was attached to the laser source housing. Fig. 3 shows a photograph of the monochromator together with the mounted LDAE.

Fig. 4 is a plot of the test results correlating the performance of our LDAE with a Heidenhain ROD-800 optical encoder with a 2 arcsec accuracy and 175 nrad resolution. The slope of the correlation data in Fig. 4 shows that our LDAE has a 0.27632 nrad count^{-1} readout sensitivity. A 100 mrad s^{-1} rotation speed was tested for a laboratory set-up in the 8° measuring range without any encoder miscounting.

It is very difficult to prove a sub-nrad system resolution experimentally in an open-loop system because of the thermal and mechanical vibration noises. However, with a commercial piezo-electrical translator (PZT) driver, such as a Queensgate NPS3330, we have made an open-loop test with two 6.6 nrad motion steps. During this test, the same sine bar and the LDAE moving target

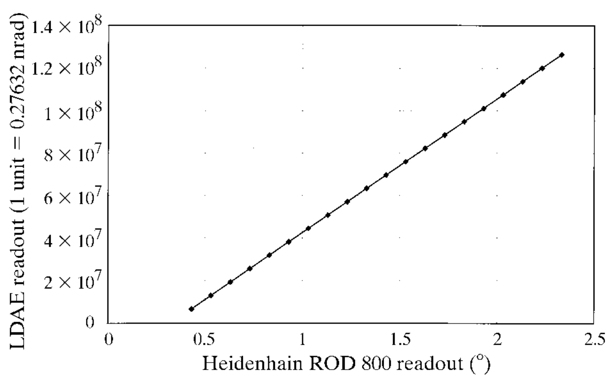

Figure 4
A plot of the test results correlating the performance of the LDAE with a Heidenhain ROD-800 optical encoder.

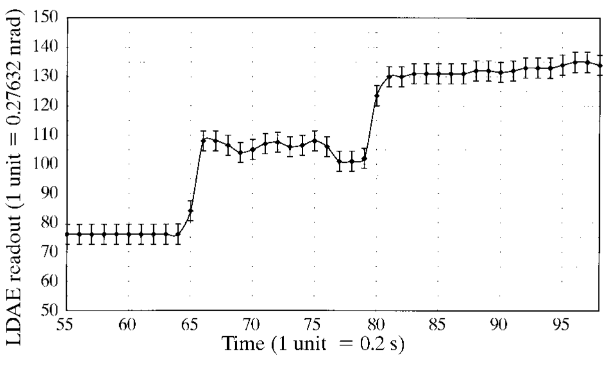

Figure 5
A plot of the test results correlating the LDAE system readout sensitivity with the Queensgate PZT driver for two 6.6 nrad jumps.

were driven by a Queensgate PZT driver. Fig. 5 is a plot of the test results correlating the readout sensitivity with the Queensgate PZT driver for two 6.6 nrad jumps. The error bars in Fig. 5 reflect the PZT driver system noise, which was about 1.9 nrad peak to peak.

4. Discussion and conclusions

We have developed a prototype laser Doppler angular encoder. 24 multiple reflections were achieved without alignment difficulty. With a customized laser Doppler displacement meter, this novel angular encoder has a sub-nrad sensitivity in an 8° measuring range. Its compact set-up [about 60 (H) $\times$ 150 (W) $\times$ 370 mm (L)] optimizes the system's antivibration performance. Two more sets of the high-energy-resolution X-ray crystal monochromator will be equipped with this novel LDAE system at the Advanced Photon Source beamline 3-ID in the next few months. In the new design, the laser head will be mounted vertically to improve the system compactness further.

Furthermore, preliminary studies for closed-loop feedback control with this LDAE have begun. Fig. 6 shows an example of this multiple-reflection optical design for angular measurement application with a closed-loop feedback system. In this set-up, a PZT-driven motion-reduction mechanism (1) is mounted on the top of a DC or stepping-motor-driven stage (2) to drive a sine-bar structure (3) for the monochromator main shaft (4). A laser Doppler displacement meter (5) with an optical-resolution extension assembly (6) is used to measure the shaft angular motion in an 8° range with sub-nrad resolution. The LDDM position signal is fed back through a digital signal processor (DSP) unit to control the PZT. The PZT drives the motion-reduction mechanism with near-ångstrom resolution to stabilize the motion.

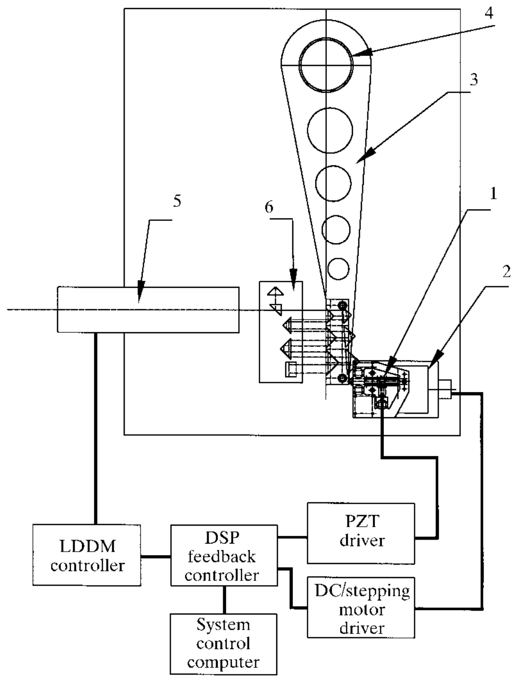

Figure 6
The multiple-reflection LDAE with a closed-loop feedback motion control system. (1) PZT-driven motion-reduction mechanism; (2) stepping-motor-driven stage; (3) sine-bar structure; (4) monochromator main shaft; (5) laser Doppler displacement meter; (6) optical-resolution extension assembly.

A system-control computer synchronizes the stage position and PZT feedback lock-in point with the LDDM position signal.

Based on this configuration, a proof-of-principle test has been performed. A PC was used to simulate the DSP feedback control with a limited bandwidth. Drastic improvement with the control feedback is observed from the test.

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