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A Novel Laser Doppler Linear Encoder Using Multiple-Reflection Optical Design for High-Resolution Linear Actuator

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ABSTRACT

A novel laser Doppler linear encoder system (LDLE) has been developed at the Advanced Photon Source, Argonne National Laboratory. A self-aligning 3-D multiple-reflection optical design was used for the laser Doppler displacement meter (LDDM) to extend the encoder system resolution. The encoder is compact [about 70 mm(H) X 100 mm(W) X 250 mm(L)] and it has sub-Angstrom resolution, 100 mm/sec measuring speed, and 300 mm measuring range.

Because the new device affords higher resolution, as compared with commercial laser interferometer systems, and yet cost less, it will have good potential for use in scientific and industrial applications.

Keywords: linear encoder, angular encoder, laser encoder, high resolution, actuator

1. INTRODUCTION

At the Advanced Photon Source, a third-generation synchrotron radiation facility at Argonne National Laboratory, x-ray scattering experiments with 10 keV or higher energies and down to sub-meV resolution have become practical.[1] In these experiments, ideally, the motion control on the monochromating crystals has to be at the nanoradian level or better. If the monochromator will be driven by a 330-mm-long sine-bar structure with a linear actuator, sub-nanometer-level resolution is needed for this actuator. However, if closed-loop feedback devices will be used, the required resolution for the actuator encoder system has to be in sub-Angstrom level over a travel range of 50 mm.

There is, at present, no commercially available linear encoder with sub-Angstrom resolution over a 50-mm measuring range. In the field of angular encoders, one of the best available products is the ROD-800 from Heidenhain, which has 175-nanoradian resolution with 360-degree measuring range when coupled with an 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, such as the Applied Geomechanics Model-520, have 10-nanoradian resolution, they 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, resolution of a few nanoradians 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 will cause complications for the system's thermal and mechanical stability.

This paper presents a novel laser linear encoder system, which is based on a laser Doppler displacement meter (LDDM)[6] and self-aligning three-dimensional (3-D) multiple-reflection optics.[7] With this new linear encoder, sub-Angstrom resolution has been attained in an 300 mm measuring range in a compact setup [about 70 mm (H) X 100 mm (W) X 250 mm (L) in size]. Modification of this encoder for a monochromator angular measurement application is also described in this paper.

2. MULTIPLE-REFLECTION OPTICS FOR THE LDDM

The laser Doppler displacement meter is based on the principles of radar, the Doppler effect, and optical heterodyning.[8] We have chosen a LDDM as our basic system, not only because of its high resolution (2 nm typical) and high measuring speed (2

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m/s) 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 sub-Angstrom linear resolution extension.

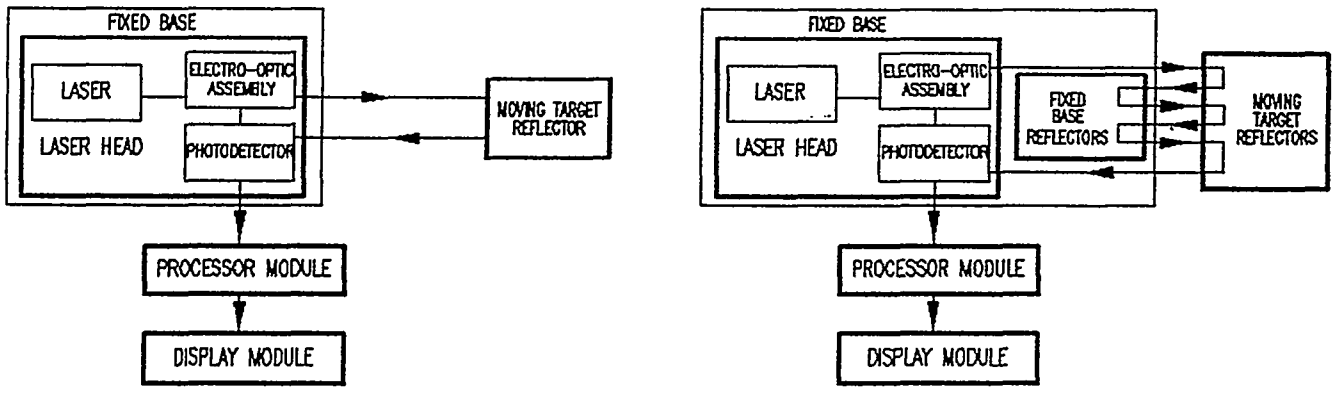
As shown in Fig. 1a, a commercial LDDM system includes four components: a laser head, a processor module, a display module, and a target reflector. The laser head houses a frequency stabilized HeNe laser, an electro-optic assembly and a photodetector, which functions as a receiver. The laser light reflected by the target is frequency-shifted by the motion of the target. The photodetector measures the phase variation caused by the frequency-shift, which corresponds to the displacement of the target. When the displacement is larger than the half-wavelength, $\lambda/2$, a counter records the total phase changes as:

$$\Delta\phi_{total} = 2\pi N + \phi, \qquad (1)$$

where N is the number of half-wavelengths, and ϕ is the phase angle less than 2π. The total target displacement, Δz, can be expressed as: [9]

$$\Delta z = \frac{c}{2f_0}(N + \phi/2\pi), \qquad (2)$$

where f_0 is the frequency of the laser; and c is the speed of the light.



(a) (b)

If we make the laser light reflecting back and forth M times between the fixed base and the target before it finally reach the photodetector, as shown in Fig. 1b, then introducing equation (2) gives

$$\Delta z = \frac{c}{2f_0 M}(N + \phi/2\pi), \qquad (3)$$

which indicates that the multiple-reflection optics provides M-times resolution extension power for the system.

Figure 2 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 reflected back and forth twelve-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 twelve-times resolution extension power for the linear displacement measurement and encoding.

As shown in Fig. 2, 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 the 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 sub-Angstrom resolution in measurements.

There are many ways to change the total number of a 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, to expand the optical path in the Z direction, one can add another one or more set of prisms as shown in Fig. 3. 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.

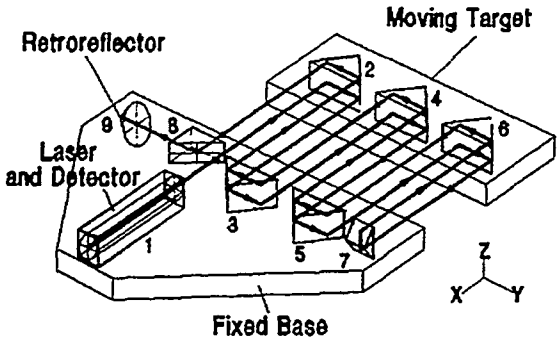


Figure 2. Configuration of a self-aligning twenty-four reflection optical design. In this figure, item 1 is the frequency-stabilized laser source with heterodyning detector, items 2 – 8 are right-angle prisms, and item 9 is the end retroreflector.

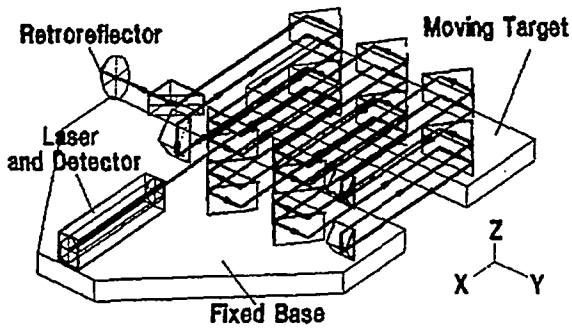


Figure 3. Configuration of self-aligning forty-eight or more reflection optical path.

3. TEST OF THE MULTIPLE-REFLECTION OPTICS FOR THE LINEAR ENCODER

A prototype LDLE system with twenty-four multiple-reflection optical resolution extension has been developed and tested at the Advanced Photon Source. As shown in Figure 4, a precision stepping-motor-driven stage has been used to test the LDLE over a 300-mm measuring range. To trace the system resolution extension power, a second regular commercial LDDM system has been applied. Figure 5 shows a plot of the test results, which proved that the prototype LDLE system provided twelve-fold resolution extension power over the 300-mm stage travel range. A 100 mm/sec stage motion speed was also tested for the prototype LDLE system without any encoder miscounting. The resolution of the custom-made commercial LDDM system, which was used during this test, was 2 nm (1 nm LSB), so that, theoretically, a 0.166 nm resolution (0.083 nm LSB) was reached by the prototype LDLE system. Figure 6 shows a photograph of the test setup with the prototype LDLE system.

It is very difficult to prove a near-Angstrom 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 6.8-nanometer motion steps. As shown in Figure 7, the LDLE moving target was mounted on a stage, which was driven by a Queensgate PZT driver. Figure 8 is a plot of the test results that correlates the dynamic performance of the PZT driver with the prototype LDLE system. The error bar on Figure 8 reflects the PZT system noise, which was about 1.1-nm peak-to-peak.

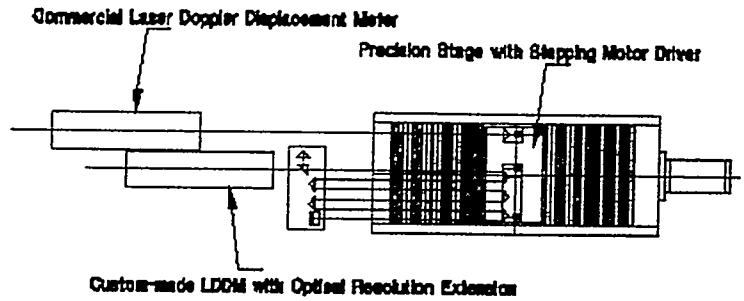


Figure 4. Schematic of the setup to test the LDLE over a 300-mm measuring range.

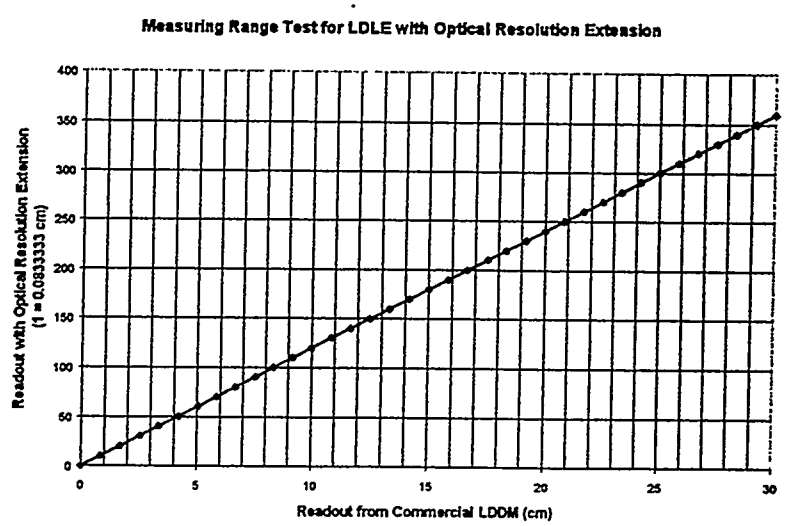


Figure 5. Plot of the test results, which proved that the prototype LDLE system provided twelve-fold resolution extension power over the 300-mm stage travel range.

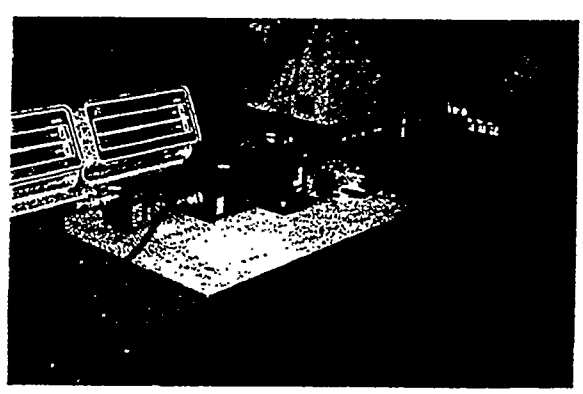


Figure 6. Photograph of the measuring range test setup with the prototype LDLE system.

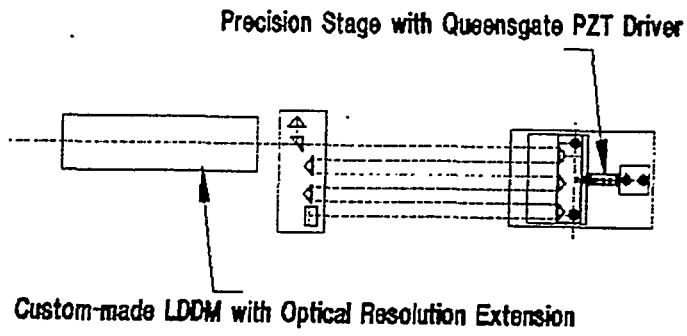


Figure 7. Setup for the LDLE test with a Queensgate PZT driver (with 6.8-nm steps).

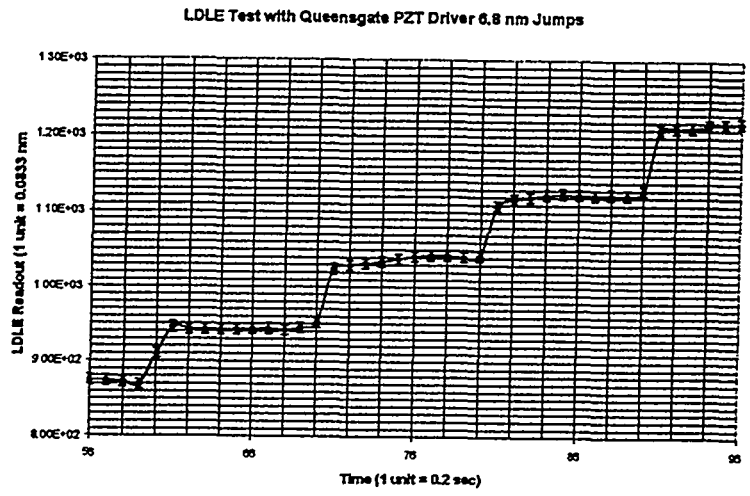


Figure 8. Plot of the test results that correlates the dynamic performance of the PZT driver with the prototype LDLE system.

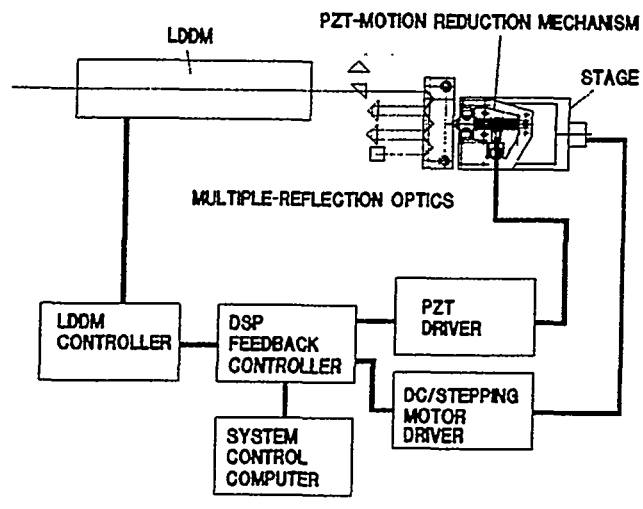


Figure 9. Example of a linear motion control application with a LDLE closed-loop feedback system.

Furthermore, based on the success of this project, preliminary studies for closed-loop feedback control with this LDLE system have begun. Figure 9 shows an example of this multiple-reflection optical design for linear measurement application

with a closed-loop feedback system. In this setup, a PZT-driven motion-reduction mechanism is mounted on the top of a DC or stepping-motor-driven stage. A laser Doppler displacement meter with an optical-resolution extension assembly is used to measure the linear motion of the stage in a 100-mm range with sub-Angstorm resolution. The LDDM position signal is fed back through a DSP unit to control the PZT. The PZT drives the motion-reduction mechanism with sub-Angstrom resolution to stabilize the motion. 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 done. 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, as shown in Fig. 10.

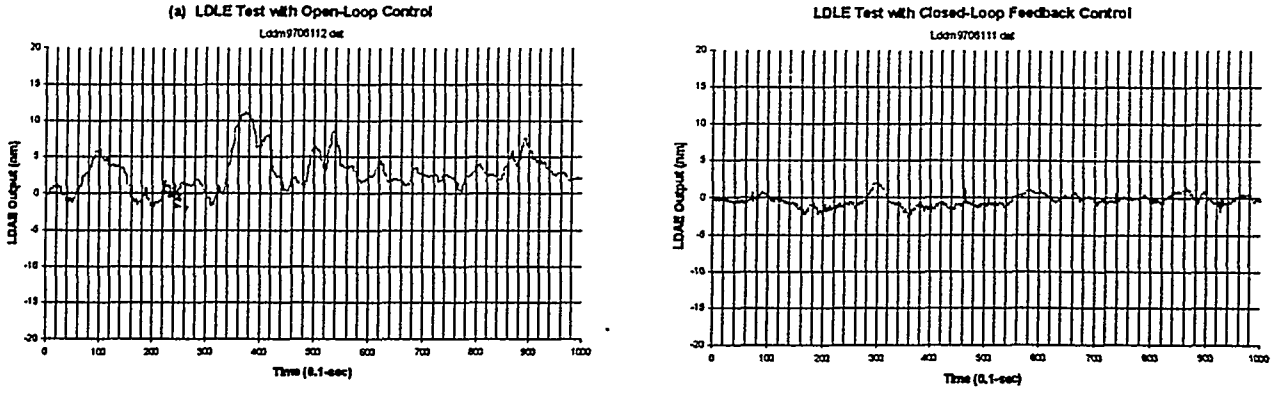


Figure 10. Results of a proof-of-principle test for the LDLE closed-loop feedback control with a limited bandwidth. (a) The stability with open-loop control, and (b) the stability with LDLE closed-loop feedback control.

4. TEST OF THE MODIFICATION FOR ANGULAR ENCODER APPLICATION

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 Fig. 2.

A prototype LDAE has been developed for high-energy-resolution x-ray scattering applications at the Advanced Photon Source undulator beamline 3-ID.[10] We have modified the monochromator (AAG-100, manufactured by Kohzu Seiki Co., Japan[11]) sine bar and related structure for the LDAE assembly. Figure 11 shows the configuration of an actual LDAE system with twenty-four multiple-reflections on the one end of the sine bar, which rotates the shaft on which the asymmetrically cut crystals are mounted. The LDAE system components can be identified as follows. A commercial laser Doppler displacement meter (LDDM) with a heterodyne detector inside is mounted on the invar fixed base, which is attached to the monochromator base, and the moving sine-bar arm is attached to the monochromator rotary shaft. A set of right-angle reflective prisms is mounted on the fixed base, and another set of prisms is mounted on the moving arm. To control the system thermal stability, a water-cooling jacket was attached to the laser source housing. Figure 12 shows a photograph of the monochromator mounted together with the LDAE.

Figure 13 is a plot of the test results that correlates the performance of our LDAE with a Heidenhain ROD-800 optical encoder with a 2-arcsec accuracy and 175-nanoradian resolution. The slope of the correlation data in Fig. 13 shows that our LDAE has a 0.276 nanoradian per count readout sensitivity. A 100 mrad/sec rotation speed was tested for a laboratory setup in the 8-degree measuring range without any encoder miscounting. Fig. 14 shows a number of 25-nanoradian steps driven by the monochromator stepping motor.

5. DISCUSSION AND CONCLUSIONS

We have developed a prototype laser Doppler linear encoder (LDLE). Twenty-four multiple reflections were achieved without alignment difficulty. With a customized commercial laser Doppler displacement meter, this novel linear encoder has sub-Angstrom sensitivity in a 300-mm measuring range. Its compact setup optimizes the system's antivibration performance.

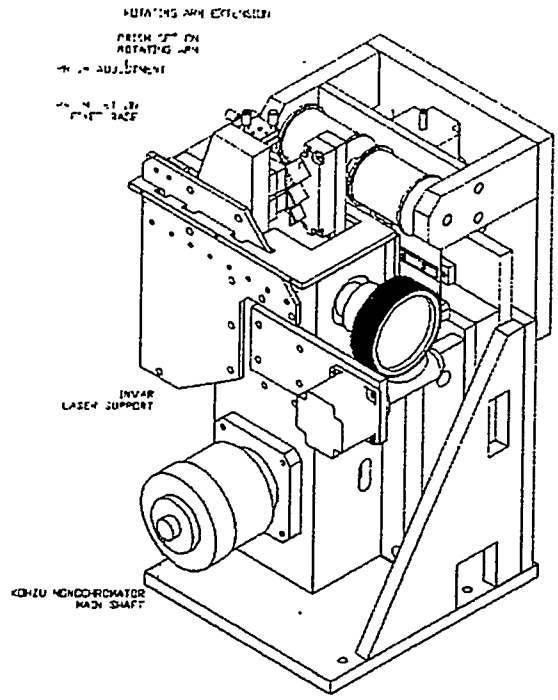


Figure 11. Configuration of the prototype laser Doppler angular encoder with twenty-four multiple-reflections on the Kohzu high-energy-resolution monochromator.

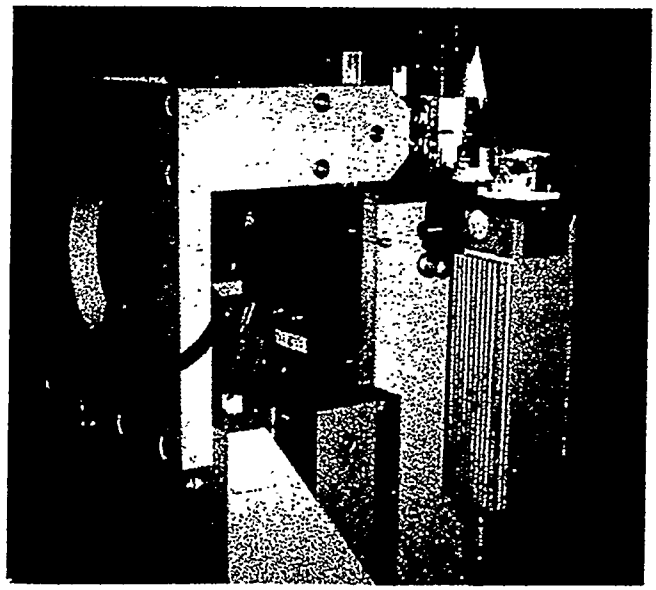


Figure 12. Photograph of the Kohzu monochromator with the LDAE.

As an application for ultra-precision angular measurement, a prototype laser Doppler angular encoder has also been developed with the LDLE technique for high-energy-resolution x-ray scattering applications. Sub-nanoradian resolution has been reached with a 330-mm sine-bar structure in a 8-degree measuring range. Preliminary studies for closed-loop feedback control with this LDLE system have begun. Development of an ultra-precision linear stage based on the LDLE and a servo system is in progress.

6. ACKNOWLEDGEMENT

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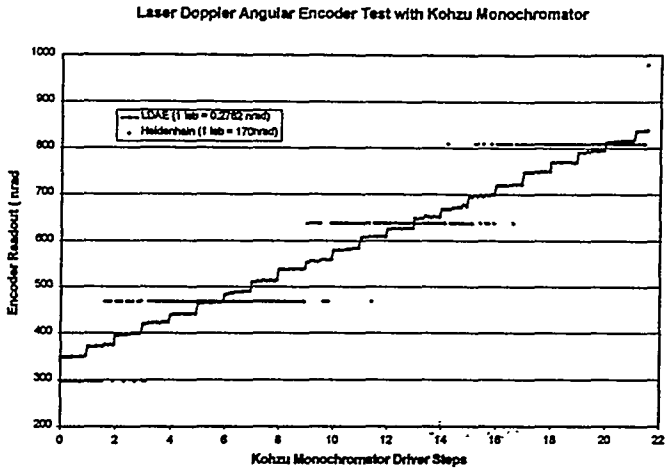

Figure 13. Plot of the test results that correlates the performance of LDAE with a Heidenhain ROD-800 optical encoder with 175-nanoradian resolution.

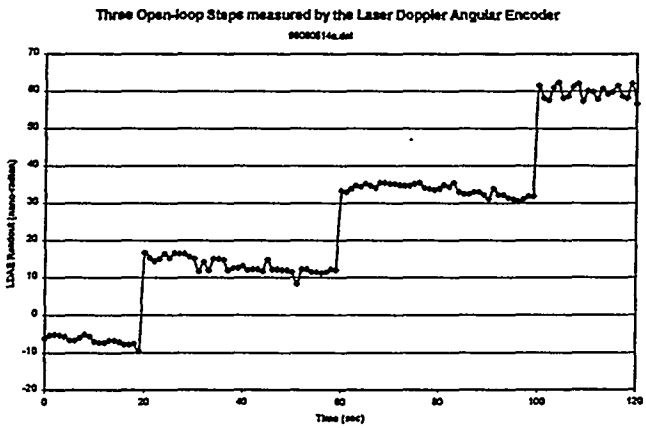

Figure 14. LDAE measurement of 25-nanoradian steps driven by the monochromator stepping motor.

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