Sub-nanometer Resolution Linear Encoder with Polarization Insensitive Laser Doppler Displacement Meter Technology and Multi-reflection Optics

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Abstract

The new nano-technology science needs transducers and actuators that have at the same time high performances and relatively affordable price. This combination it is made possible by the laser Doppler displacement meter (LDDM) [1,2] technology because of the polarization insensitive single coaxial beam, it can use the multi-reflection optics, that multiply the laser resolution by the number of bouncing. It is possible to realize closed loop positioning systems with very high resolution and compact dimensions, in order to realize positioning systems for industrial or scientific applications. LDDM technology has the combination of the single coaxial beam laser, high speed, low noise and high sensitivity. All the above characteristics are necessary for the implementation of the sub-nanometer resolution and large movement range. In this paper will be illustrated shortly the LDDM laser technology, the practical implementation with the optical multiplier, and the LDDM application for hard x-ray nanoprobe at the synchrotron radiation facility.

1. Introduction

For a laser interferometer type measurement, typical resolution is 2-10 nm. However, because of the air circulation, or turbulence, the effective laser beam path length (OPD) is fluctuating. This fluctuation limited the accuracy of the laser measurement. Long time-average has been used to minimize the effect of air turbulence. However, too much averaging may cause a time-lag and inconvenience in the measurement. The resolution of a laser interferometer is limited by non-linearity and electronic noise. For higher performances a resolution of 0.62 nm is reached dividing by 1024, but a very high S/N ratio is required. The signal is affected by air turbulence, vibration and acoustic noise and increasing the resolution by increasing the division factor only is very difficult to be achieved.

2. LDDM technology

The polarization insensitive LDDM is based on the principles of radar, the Doppler effect and optical heterodyning. Similar to a Doppler radar, a target or retroreflector is illuminated by a laser beam. The light reflected by the retroreflector is frequency-shifted by the motion of the retroreflector. A phase detector measures the phase variation, which corresponds to the displacement of the retroreflector inside half wavelength. A counter records the total phase change. The phase detector output is a linear function so can be directly converted by an A/D and summed to the counter. The LDDM has a single coaxial beam with single aperture. It is compatible with a very small retroreflector or flat mirror as target. The coaxial beam in combination with large tolerance of misalignment can be used in a various combination of optical arrangement including multiple-pass for sub-nanometer resolution and stability.

3. Multiple-pass optics for one-dimensional measurement

A multiple-pass is an optical arrangement, with the laser beam reflected back and forth between the retroreflector target and some mirrors or prisms mounted stationary with the laser head. It has been shown that multiple-pass optical arrangement can increase the resolution, and reduce the effect of air turbulence.

The multiple-pass optical arrangement developed by Optodyne can easily be achieved by attaching an optical adapter (an accessory) to the single aperture laser head (MCV-500 laser calibration system) and using a 25mm diameter retroreflector as target as shown in Fig. 1. The number of passes between the optical adapter and the retroreflector is increased by a factor of 6. That is, one mm displacement of the retroreflector will become a 6 mm increment of the effective optical path length. Hence the resolution is increased by a factor of 6 and the air turbulence is averaged over the 6 parallel paths. For a MCV-500 laser system, the standard range is more than 12m. Hence the range becomes 2m with the 6-pass optical adapter. Since the maximum velocity is 5 m/sec, the maximum velocity with the 6-pass optical adapter becomes 800 mm/sec.

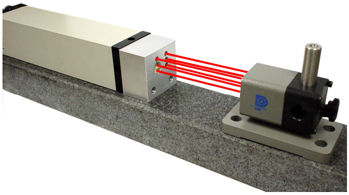

Fig. 1: Photograph of a 6-pass optical arrangement.

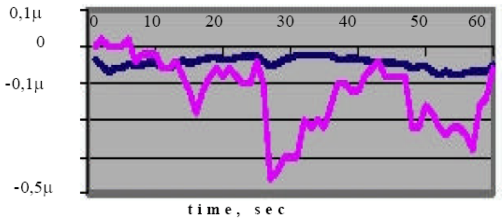

Fig. 2: Effect of air circulation on a 6-pass optical arrangement versus a single pass optical arrangement.

To verify that the multiple-pass optical arrangement can reduce the effect of refractive index change of air, two laser systems were set up co-axially with both retroreflectors mounted together and with equal distances from the laser heads. A typical result is shown in Fig. 2. The heavy line is the fluctuation in the 6-pass optical arrangement and the light line is the fluctuation in a single-pass optical arrangement. The effect of air circulation or the refractive index change, is reduced considerably in the 6-pass optical arrangement.

At the Advanced Photon Source (APS), Argonne National Laboratory (ANL), a one-dimensional laser Doppler linear actuator system with 1-angstrom closed-loop control resolution and a 50-mm travel range has been developed and tested using Optodyne LDDM system with ANL developed 12-reflection optics, high-stiffness weak-link mechanism, and DSP-based controller [3].

4. Multiple-pass optics for three-dimensional measurement

A hard x-ray nanoprobe instrument with nanometer-scale active vibration control has been constructed as the centerpiece of the x-ray characterization facilities at the APS for the Center for Nanoscale Materials (CNM) at ANL. A specially designed, custom-built LDDM system provides two-dimensional differential displacement measurements with nanometer scale resolution between the zone-plate x-ray optics and the sample holder [4]. The LDDM heterodyning detector is housed coaxially inside the frequency-stabilized laser source, with the self-aligning 8-reflection optics, the laser beam is reflected back and forth eight times between the fixed base and the moving target.

5. Future work and summary

An U.S. DOE Cooperative Research and Development Agreement (CRADA) between ANL and Optodyne, Inc. has been established to develop a prototype LDDM system with ultra-low noise level for linear measurements to sub-nanometer resolution for synchrotron radiation applications. To achieve a higher signal-to-noise ratio, we have improved the heterodyne efficiency and reduced the detector shot noises by proper shielding and adding a low-pass filter. A ~ 1 nm LDDM output noise floor has been demonstrated using the new LDDM system with single reflection optics as shown in Figure 3. Test of the new LDDM system with multiple-pass optical arrangement and 0.1 nm scale closed-loop feedback control is in progress.

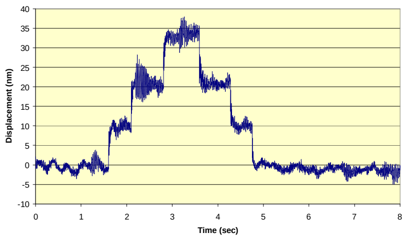

Fig. 3: Open-loop 10-nm-steps measured by the new LDDM system with single-pass optics.

Acknowledgments

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References

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