High-accuracy short-range displacement metrology

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Abstract

Many different techniques have been developed for precision measurements of sub-mm displacements. This paper will provide a brief overview of such techniques and compare relevant performance characteristics and limitations.

The performance of a fiber-based sensor system that addresses many of the limitations of existing displacement measurement technologies will then be described. This research system is an optical fiber based, multi-channel interferometer system that combines high-accuracy displacement measurement capability with absolute distance measurement over a range of 500 µm, with a displacement measurement uncertainty (k=2) of 4 parts per million. The ability to determine the absolute distance of the target relative to the sensor datum provides a highly repeatable (~2-3 nm) position datum, e.g., for use in establishing a 'home' position. Such a system could be used in demanding applications requiring a multitude (~60) of thermally passive, electrically immune, extremely compact sensors and exceptional long-term drift performance

1 Overview of technologies

Sensors for the measurement of displacement based on a number of different physical principles have been developed for a variety of applications. This paper primarily concerns itself with commercially available systems capable of resolutions of ~100 nm and below. From a review of commercially available displacement sensors[1], displacement sensors may be divided into two broad categories - Type I, where range and resolution are not coupled and Type II, where they are. Examples of Type I sensors include interferometric sensors and encoders, where the resolution is

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[1] Based on data from the manufacturer's literature for commercial systems

independent of the range of measurement, resulting in extremely high dynamic ranges (range/resolution). Typical Type II technologies include chromatic aberration based sensors, confocal devices, reflectance based fiber sensors, triangulation based devices, inductive (LVDT) and capacitive sensors, etc. Encoders and free-space interferometric sensors however, have several drawbacks when compared to Type II technologies. These include the lack of an intrinsic means of establishing the distance of the target from the sensor and the ability to function as homing sensors without modification (index marks, supplementary home sensors, etc.). Further, they tend to have relatively large sensor packages and in the case of interferometers require a complex arrangement of beam directing optics. Therefore, for short range displacements, Type II sensors are often preferred, despite the active (heat dissipating) nature of many of these sensors. Fiber-based interferometric sensors incorporate the best features of both classes of sensors and combine relatively large dynamic range and high resolution (characteristic of Type I sensors) with high-accuracy absolute distance measurement and high-precision homing (improving on Type II sensors). Use of optical fiber results in a passive, EMI immune, compact sensor package.

2 Displacement/absolute distance sensor system

This section describes the performance of a test system[2] that addresses many of the limitations of Type I sensors and improves on many of the desirable aspects of Type II sensors.

A detailed description of the working of the system may be found elsewhere [1]. The architecture of the system allows for applications that require simultaneous measurement over short ranges of a multiplicity of channels (~60) at a bandwidth of many kHz. The system architecture is optimized to provide completely passive sensors, high system reliability and low cost per channel. This is achieved by partitioning the system into two parts: the control unit and the sensors. This concentrates heat generating components and cost in the control unit, leaving the sensors completely passive, and minimizes the incremental cost of adding channels.

[2] Protected by U.S. and foreign patents or patents pending

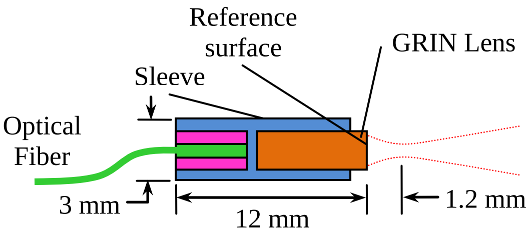

Figure 1 Schematic of sensor

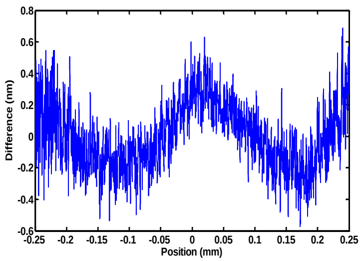

Figure 2 Displacement measurement performance

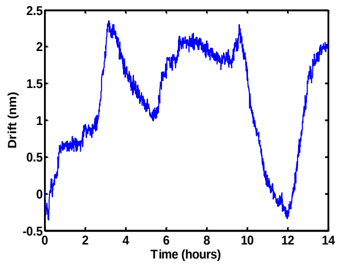

Figure 3 Stability of absolute distance measurement

Further, all components that may require maintenance or replacement are in the control unit while the high-reliability sensors can be embedded within the application.

The sensors leverage commonly available telecom components in terms of size, cost and reliability, resulting in extremely compact (ϕ3 X 12 mm length as shown in Figure 1) and reliable sensors. Optical fiber connections confer flexibility on the routing and immunity to electromagnetic interference (EMI), as does the optical interference based operation of the sensor.

The system operates in two distinct modes: absolute distance and displacement measurement. In the absolute distance mode, in contrast to most displacement interferometer systems where the absolute distance of the target in unknown, the distance of the target from the reference surface may be determined. This provides the ability to return the target to a predetermined distance from the reference surface, i.e., a 'homing' functionality in the presence of momentary beam interruption and upon restarting the system. In the displacement mode, changes in position, i.e., displacement, may be determined. In combination, the displacement of a target from a known initial position may be determined.

Displacement measurement performance is evaluated by comparing the results of simultaneous measurement of a common target by a commercial displacement interferometer (Zygo ZMI-4000) [2]. The difference between the two systems is shown in Figure 2. When taken in context of the uncertainty in the measurand (k=2) of 0.5 nm, Figure 2 suggests agreement to within the uncertainty in the difference, i.e., to within 1 ppm.

Unlike many other displacement sensors where the sensor mount defines the measurement datum, the sensor design provides for a well defined and mechanically accessible datum (reference surface in Figure 1) with reference to which measurements are made. In addition, specialized sensors can be designed that permit measurements relative to an user-defined external datum.

The stability in absolute distance mode over a period of several hours is evaluated by repeatedly measuring a stable etalon. This is a measure of the stability of a previously established 'home' position. The measured stability is < 3 nm over a 14 hour period as shown in Figure 3.

3 Summary

A brief overview of displacement measurement technologies has been presented. A fiber-optic interferometric sensor that provides a highly-desirable set of performance characteristics has also been briefly described.

References:

[1] V. G. Badami *et al*, Compact, Multi-channel, Fiber-based Absolute Distance Measuring Interferometer System, *Proc. 24th ASPE Annual Meeting*, Monterey, CA, 2009, pp. 67-70.

[2] V. G. Badami and C. D. Fletcher, Validation of the Performance of a High-accuracy Compact Interferometric Sensor, *Proc. 24th ASPE Annual Meeting*, Monterey, CA, 2009, pp. 112-115.