High-accuracy short-range displacement metrology

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Abstract

We provide a brief overview of precision measurements of sub-mm displacements and compare relevant performance characteristics and limitations, followed by a detailed analysis of a 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.

1 Overview of technologies

Sensors for the measurement of displacement based on a number of different physical principles are available for a variety of applications. Here we consider systems capable of resolutions of ~100 nm and below. From a review of commercially available systems, 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 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. Encoders and free-space interferometric sensors however, have several drawbacks when compared to Type II technologies. These drawbacks 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 Fiber-optic distance sensor system

This section describes the performance of an experimental system as part of our research into solutions that address many of the limitations of Type I sensors and improves on many of the desirable aspects of Type II sensors.

The system allows for applications that require simultaneous measurement over short ranges of a multiplicity of channels (~60) at a bandwidth of many kHz [2]. The system architecture provides for completely passive sensors, high system reliability and low cost per channel 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.

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 instrument determines the distance of the target from the reference surface. This

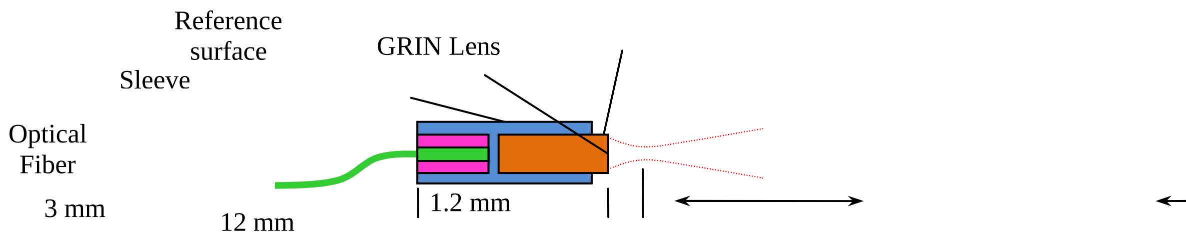

Figure 1 Schematic of sensor

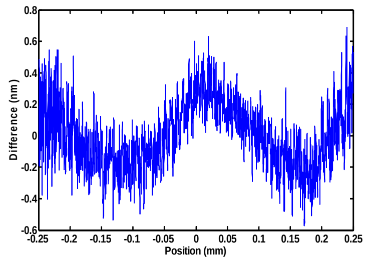

Figure 2 Displacement measurement performance

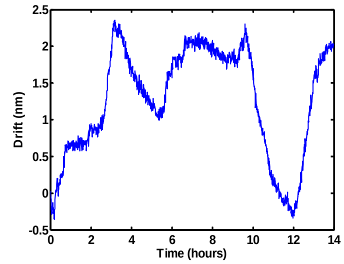

Figure 3 Stability of absolute distance measurement

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. The displacement mode measures changes in position. This combination establishes the absolute displacement of a target from a known initial position.

Simultaneous measurement of a common target by a commercial displacement interferometer (Zygo ZMI-4000) quantifies the displacement measurement performance of our experimental fiber sensor system [3]. 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 new 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.

Repeated measurements of a stable etalon demonstrate the stability in absolute distance mode over a period of several hours. This is a measure of the stability of a previously established 'home' position. Figure 3 shows a measured stability of < 3 nm over a 14 hour period.

3 Summary

The performance of a fiber-based sensor system addresses many of the limitations of existing displacement measurement technologies. Our research system determines the absolute distance of the target relative to a datum with excellent repeatability of 2-3 nm, 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.

References:

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[2] 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.

[3] 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.