Fiber Optic Displacement Sensor

P.G. Davis and I.J. Bush
Optiphase Inc.
7652 Haskell Ave.
Van Nuys, CA 91406

G. S. Maurer
Raychem Corporation
300 Constitution Drive
Menlo Park, CA 94025-1164

ABSTRACT

A novel low cost interferometric displacement sensor has been developed which tracks distance from the tip of a fiber optic probe. A unique interrogation technique is used which produces a 32-bit phase word, giving the system a dynamic range > 10^9. Therefore, a displacement resolution of < 0.01 nm can be achieved with a full range of 6 mm. The measurement range can be extended beyond 10 m by simply adjusting the digital fringe counter and sacrificing resolution yet maintaining the > 10^9 dynamic range. Demodulation rates of 40 kHz have been achieved which facilitates dynamic measurements. Results from an application to hard disk (HD) profilometry are presented.

I. INTRODUCTION

Interferometry is one of the most accurate methods to measure distance due to the small size of an optical wavelength (1 μm), and the high accuracy of optical phase measurements (1 μRad/rt-Hz). This translates into displacement resolutions as small as 0.0001 nm. Such measurements are currently being made for the Laser Interferometer Gravitational-Wave Observatory (LIGO)[1]. Although these incredible resolutions are possible, for most applications of a displacement sensor, this type of sensitivity is not required. Instead, what is desired is a dynamic measurement with a large dynamic range. This can also be accomplished with interferometry and the proper interrogation and demodulation scheme.

The interrogation and demodulation technique utilized for performing large angle or fringe counting interferometry with sub-fringe resolution involves a phase generated carrier (PGC) interrogation followed by a digital demodulation scheme. The nonlinear interrogation signals are processed into a signal which is linear with optical phase. This direct measurement of optical phase is then proportional to distance as scaled by the wavelength and the index of refraction.

The displacement sensor application presented is the measurement of the surface of hard disks. As hard disk manufacturing technology improves, the requirements for hard disk substrates is becoming more stringent. Not only must the surface be free of defects but the disk dynamics must be understood and controlled. Measurements of hard disks will be presented as an example of the capability of this displacement sensor since it both illustrates the resolution, dynamic range, and dynamic measurement capabilities of the sensor.

II. PROBE DESIGN

An inexpensive probe design was developed so that multiple probes could be used without a prohibitive rise in expense. The probe consists of an optical fiber held close to the surface in question so as to create a low finesse Fabry-Perot cavity between the end of a polished fiber tip and the surface as shown in Figure 1. The two beams which combine to form the interferometer are the 4% internally reflected beam from the end of the fiber and the beam that is reflected from the surface being probed. Since no lenses were used, the probe is not only robust mechanically but also insensitive to angular misalignments. With the 4% reflection from the end of the optical fiber, a captured reflection from the surface of 1% of the incident light still results in 20% visibility of the interferometric signal and with the PGC demodulation scheme even 1% visibility will result in accurate demodulation. Since the optical path difference is simply the round trip distance traveled by the light that is reflected by the surface in question, the measured optical phase is directly proportional to the distance between the end of the probe fiber and the surface being probed.

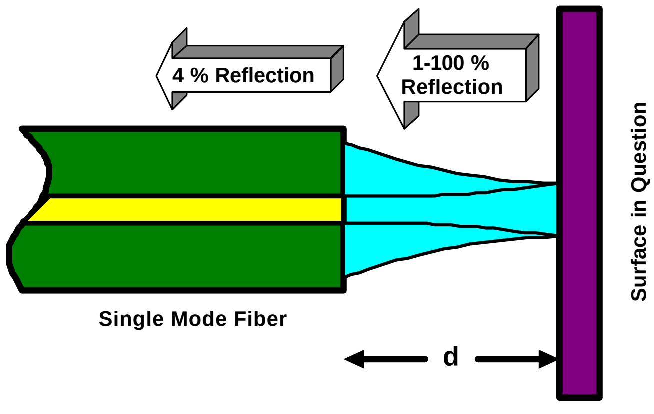


Figure 1: Probe Schematic

As was mentioned above, a PGC interrogation scheme is used for demodulation. To generate the PGC signal with the Fabry-Perot interferometer, the probe fiber was mounted within a PZT cylinder that vibrated the fiber so as to modulate the gap between the fiber and the surface. A picture of a probe is shown in Figure 2. The resulting interferometric phase can be expressed as:

$$\theta(t) = \beta \sin(\omega t) + \frac{4\pi}{\lambda} \cdot d \qquad (1)$$

where β is the modulation depth, λ is the optical wavelength, and *d* is the distance between the fiber tip and the surface. Using a π modulation scheme, that is $\beta = \pi$, resulted in the requirement that the gap be modulated by 775 nm pk-pk for a 1550 nm source. The measured phase is then proportional to the mean distance between the probe and the surface.

Interferometric interrogation and optical phase measurements were accomplished using the Optiphase Inc. OPD-200 digital demodulator. This instrument produces a 32-bit phase word with the LSB corresponding to 6 µRad. The demodulation rate was limited by the resonance of the PZT to 40 kHz, however, the demodulator is capable of rates up to 95 kHz. With the 32-bit phase word, the instrument's dynamic range exceeds 10^9. When applied to the displacement sensor, a range of 6 mm can be achieved with 0.001 nm resolution.

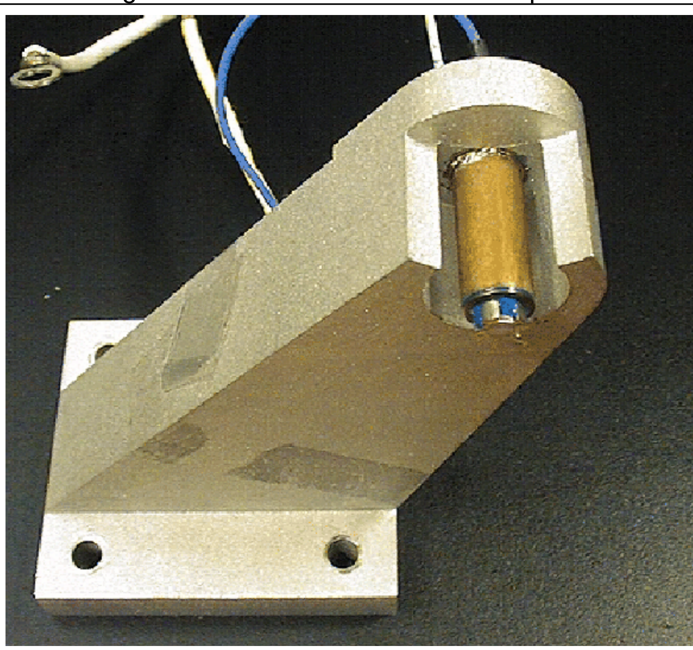


Figure 2: Picture of HD Probe

The OPD-200 demodulator controls the optical interrogation scheme as depicted in Figure 3. An Erbuim source, which produces up to 10 mW of optical power, was used as the light source. With this single high power source, the capability of implementing many simultaneous probes exists. For simplicity, we have limited the discussion to a single probe. The 1550 nm light was directed to the probe through a 50/50 coupler. Since the interferometric signal is produced by light from the fiber

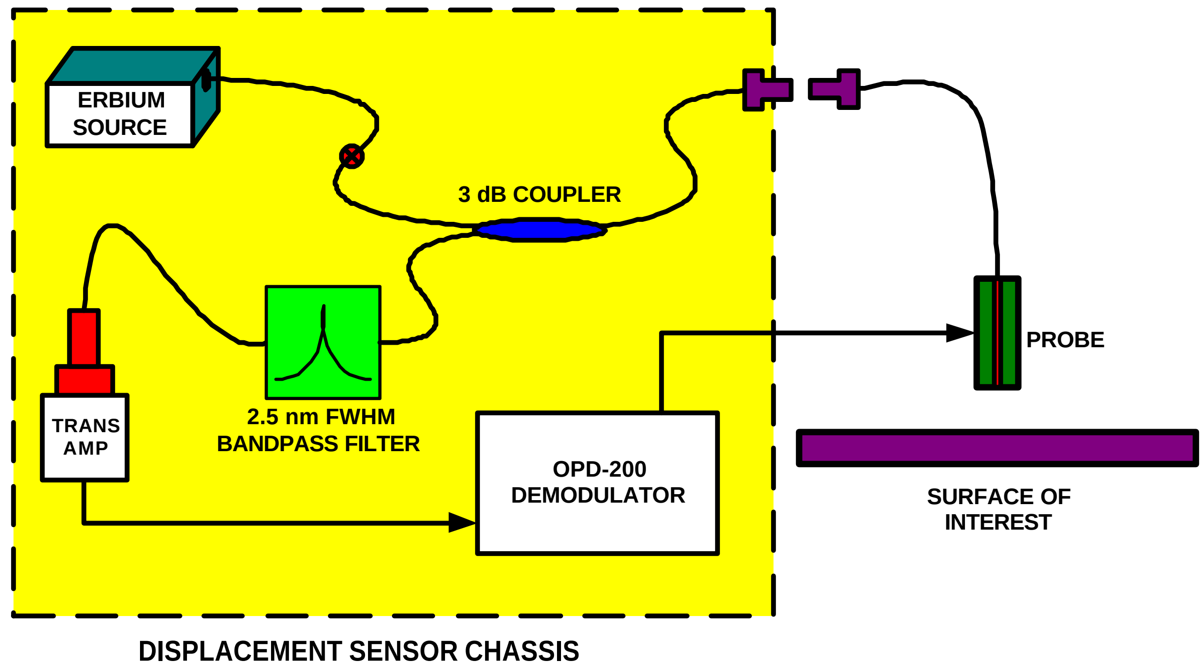


Figure 4: Optical Interrogation Scheme for the Displacement Sensor

tip interfering with light from the surface, the entire fiber length to the probe is common path for the interferometer and can be made any length desired without degrading the signal. The return light is then bandpass filtered in order to extend the coherence length of the light so that the signals from the fiber tip and the surface will interfere. In order to capture enough light from the surface, the fiber is typically held within 200 microns of the surface. In addition, the coherence length must be longer than 200 microns for the two beams to interfere. As determined by the Fourier relationship, the optical bandwidth must be < 5 nm FWHM to result in a 200 µm coherence length. Therefore, a 2.5 nm FWHM filter was chosen.

There are many exceptional properties of this probe design. First, the probe is inexpensive. The use of standard Telco fiber and PZT technology allows for multiple probes to be affordable. Secondly, since the Telco fiber is common path to the interferometer, the probe length can be made an arbitrary length for remote deployment. Thirdly, since the optical wavelength is fixed, the gap modulation required to achieve a modulation depth of π is likewise fixed and thus the demodulation is independent of the gap size. Therefore, given a coherent source, the PGC demodulation can be performed from < 200 µm to

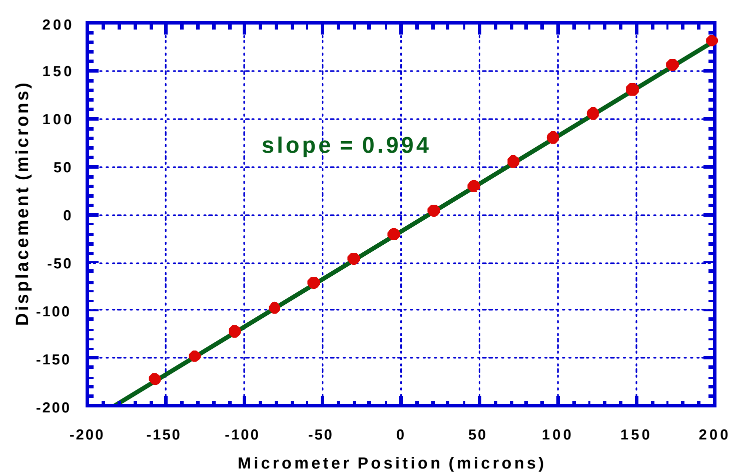


Figure 3: Linear Displacement Plot

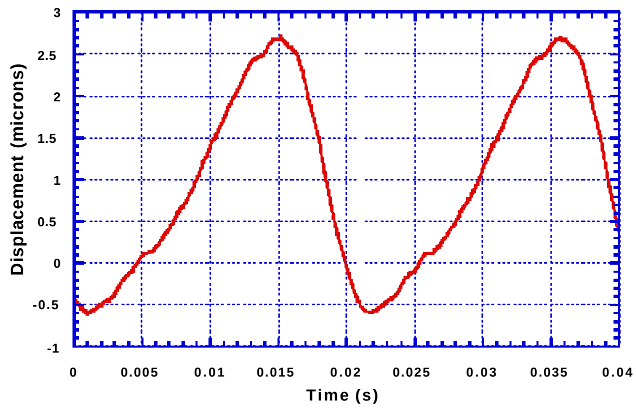
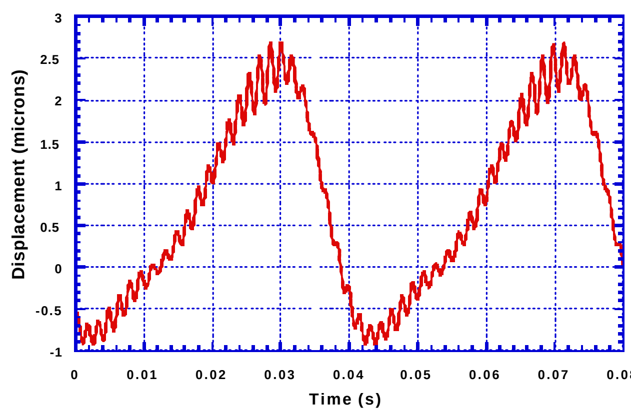


Figure 5: Ceramic Disk Spinning at 2900 rpm

many m without adjusting the modulation depth. Finally, by using the probe without a lens near the surface to create a low finesse Fabry-Perot, the probe is insensitive to angular alignment or interferometeric errors due to multiple reflections. For these reasons the fiber optic displacement sensor is a robust measuring device which is both relatively inexpensive and easy to use.

III. INITIAL MEASUREMENTS

Using the probe shown in Figure 2, a benchtop calibration was performed to verify the linearity of the sensor over a large range without user intervention. Again, no lenses were used. The probe was set up at about 100 microns from the surface and then moved away. As the probe was moved further from the surface, the amount of optical power captured from the surface dramatically decreased with no effect on the optical phase measurement. This is due to the demodulator's insensitivity to amplitude changes. The probe was moved up to 350 microns away from the surface which effected more than a factor of 10 reduction in captured light from the surface and therefore more than a factor of 10 reduction in fringe visibility. The measured displacement vs micrometer position is graphed in Figure 4.



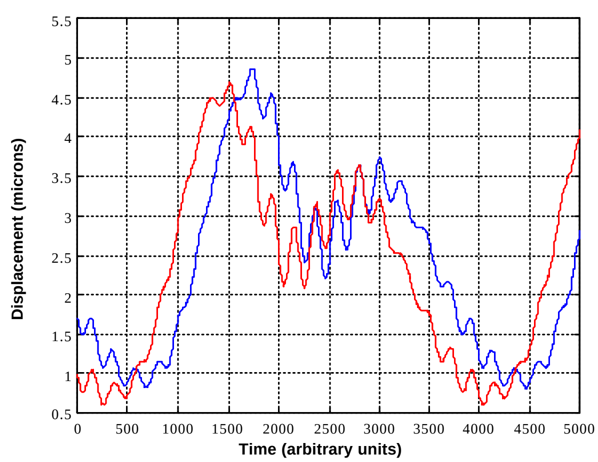


Figure 7: Dual Probe Measurement of a Ceramic Disk

IV. APPLICATION TO HARD DISKS

In applying the displacement sensor to hard disk measurements, our goal was to demonstrate dynamic axial runout measurements as the disks were spun at various speeds. This system was tested with three substrate materials, aluminum, glass, and ceramic. Examples of the measurements on a ceramic substrate are shown in Figures 5 and 6. The graphs show the difference in the dynamic flatness characteristics of the disk as it is spun at two different rotational rates. Although the runout is approximately the same for both running speeds, indicating that the disk was not flat, at 1455 rpm the disk appears to have a high order ripple.

To further the understanding of the disk dynamics, a second probe was mounted at approximately a 60 degree separation from the first probe. Both probes were then used to simultaneously monitor the disk surface. As shown in Figure 7, the disk runout as measured by both probes was the same but displaced in time as is expected given the angular separation of the probes relative to the disk center. This further collaborates with the above statement that the disk is not flat. However, the high frequency fluctuations observed appear to be phased independent of the angular separation of the probe. This indicates that the entire disk is most likely moving up and down in time rather than synchronous with a disk revolution. Such a disturbance can be enhanced by a mechanical resonance of the disk.

V. CONCLUSIONS

The displacement probe has been successfully demonstrated and applied to the study of hard disk dynamics. These probes are inexpensive to make and can be multiplexed with one light source. Currently the dynamic measurements are limited by both the probe mechanics and the demodulator electronics to less that 100 kHz but future design should be successful in implementing diagnostics in the MHz range.

VI. ACKNOWLEDGMENTS

The authors wish to acknowledge the efforts of Steve Dillinges of Raychem Corp. in supporting the laboratory tests and Joel Finegan of Raychem Corp. for his insights in the behavior of the hard disk dynamics and the work of Mirko Invancevic of Optiphase Inc. in building the probes.

[1] S. Kawamura, Proceedings of the TAMA Conference (1996)