A Compact Industrial Distance Measuring Interferometer System

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Distance Measuring Interferometry (DMI) plays a key roll in the most demanding areas of precision engineering. Familiar applications include microlithography for integrated circuits, where the decreasing minimum feature size and manufacturing cost reductions provides the impetus for developing more accurate positioning stages. Machine tools circuit inspection systems that presently rely on encoders or glass scales are beginning to experience a similar demand for the higher accuracy. In many of these systems, the encoders and/or scales are the most significant contributors to measurement errors. There is consequently an open need for a DMI having greater accuracy and reliability than encoders but at a more accessible cost and size when compared to traditional heterodyne systems. We have therefore developed a new compact industrial DMI to assist in the transition from encoders to high-precision heterodyne interferometry. The new Zeeman laser based system has resolutions down to 10 nm and accommodates three axes of metrology at stage velocities up to 0.5 m/s.

Introduction

The authors listed represent the development team responsible for various parts of this project. This paper is organized as follows; it starts with a design overview and project goals, followed by some key calibration data, which demonstrates the performance capabilities of this new DMI and ends with a description of the error budgets and sub-systems.

Design Overview

Figure 1 shows a simple single axis DMI system consisting of the laser head, interferometer assembly, phase interpolator board, and a moving target mirror. The output from the laser head is two linearly polarized beams of light ($\lambda_{1,2}$=632.991 nm) which are separated in frequency by 3.65 ± 0.35 MHz. The polarization states are orthogonal to each other. The two components are separated in the interferometer. One component travels a constant path in the interferometer assembly while the other has a path length that is dependent upon the position of the target mirror. The two components rejoin inside the interferometer assembly, after traveling their separate paths, and are mixed and launched into a fiber optic cable. The other end of the fiber optic cable plugs into a fiber optic receiver that is mounted on the phase interpolator board. This optical signal will hereafter be referred to as the measurement signal. Exiting from the rear of the laser head is the optical phase reference signal, which is also directed to a fiber optic receiver on the phase measurement board via a fiber optic cable. This signal is hereafter referred to as the reference signal. As the target mirror moves in the indicated directions, the phase between the measurement and reference signals changes. The changing phase is converted to A-QUAD-B or UP/DOWN PULSES output data formats. The A-Quad-B output is comprised of two signals (for discussion purposes these will be referred to as S_0 and S_1) that are separated in phase by 90 degrees. The absolute phase angle of S_0, and corresponding absolute phase angle of S_1, is proportional to the displacement of the target mirror. By monitoring signals S_0 and S_1, changes in the position of the target mirror and the direction of motion can be determined. The up/down pulses output is simply two signals that pulse independently of each other but dependent on the target mirror motion. One pulse is generated for every least count of the phase measurement electronics. The phase interpolator board is configurable for least count resolutions of $\lambda/64$, $\lambda/32$, $\lambda/16$, and $\lambda/8$. The system was designed to support up to three measurement axes simultaneously with the measurement errors not to exceed 100 nm 3σ over any 24-hour period of time. This accuracy specification constrains the temperature excursions of the optical beam paths to ± 0.1 °C and the measurement range to 0.3048 m. We designed to a maximum output data rate of 16 MHz to accommodate a variety of third party servo controller boards. This data rate limits the velocity at the higher resolutions while the heterodyne frequency (3.65 MHz) limits it at the lower resolutions.

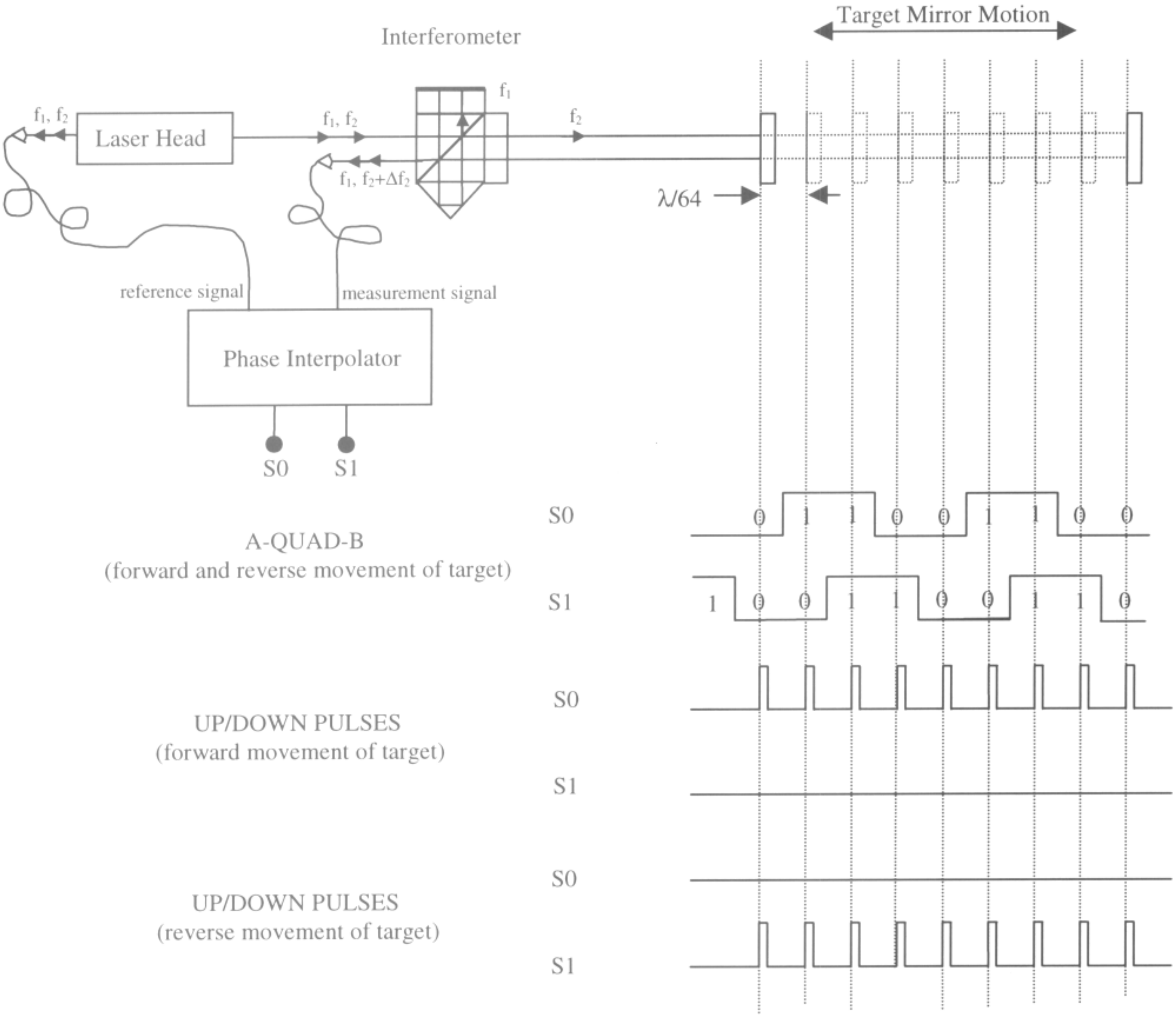
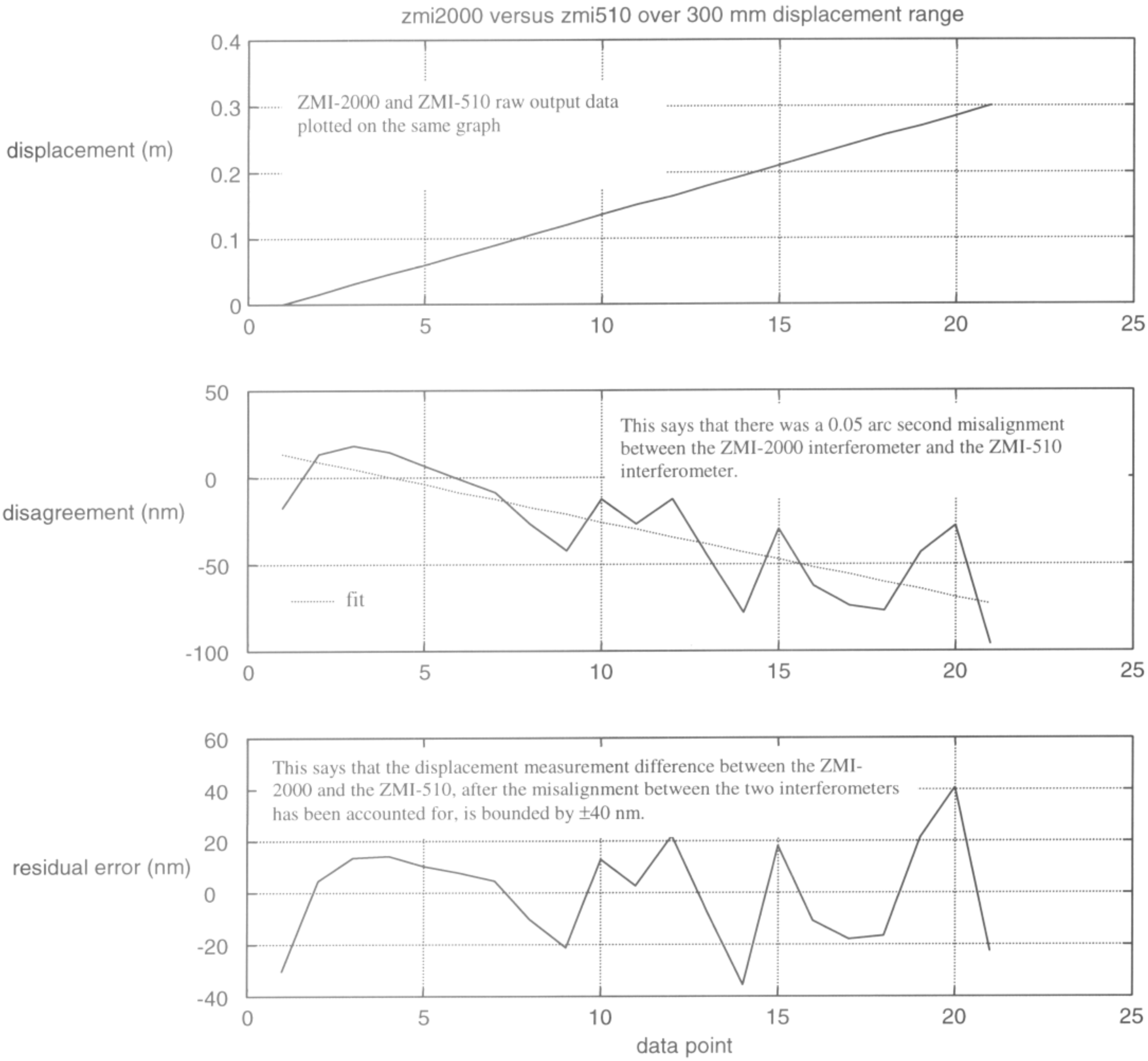


Figure 1 – typical distance measuring interferometer system

Performance

The performance of this DMI system was characterized in the labs of North Carolina's Center for Precision Metrology[1]. The new compact DMI was calibrated against the ZMI-2000 distance measuring interferometer system[2]. A common target mirror was mounted to the X-slide of a Leitz coordinate measuring machine which is located in the Center's temperature controlled metrology lab. The temperature is conveniently controlled to ± 0.1 °C. The two interferometers were aligned and measurements were taken throughout a 305 mm range of travel. This simultaneous linear displacement accuracy test then calibrates the newly developed compact DMI against the old proven DMI. The results of the test are shown in figure 2. Note that the new DMI more than meets the ± 100 nm accuracy specification.



ZMI-2000 and ZMI-510 raw output data plotted on the same graph

This says that there was a 0.05 arc second misalignment between the ZMI-2000 interferometer and the ZMI-510 interferometer.

This says that the displacement measurement difference between the ZMI-2000 and the ZMI-510, after the misalignment between the two interferometers has been accounted for, is bounded by ±40 nm.

Figure 2 – system accuracy acceptance test data

Laser Head

The laser head is a single mode Zeeman split laser that samples light from the rear of the laser tube for stabilization. A low cost, but high performance optical frequency stabilization scheme was developed for the system. The results of this effort are shown in figure 3, which shows the frequency difference between the vertically polarized components of our new laser head and a frequency stable reference. Note that the frequency instability is less than 0.6 MHz (about 1.2 ppb) peak to peak over 2 hours. The DMI measurement error allotment to the laser head was about 12 nm. The minimum output optical power specification is 250 μW. The laser head dissipates about 6 Watts during normal operation. The laser head is 10.5 ″ x 2.5 ″ x 2.5 ″ and weighs about 2 ¼ pounds. The beam diameter is 4 mm to the $1/e^2$ points.

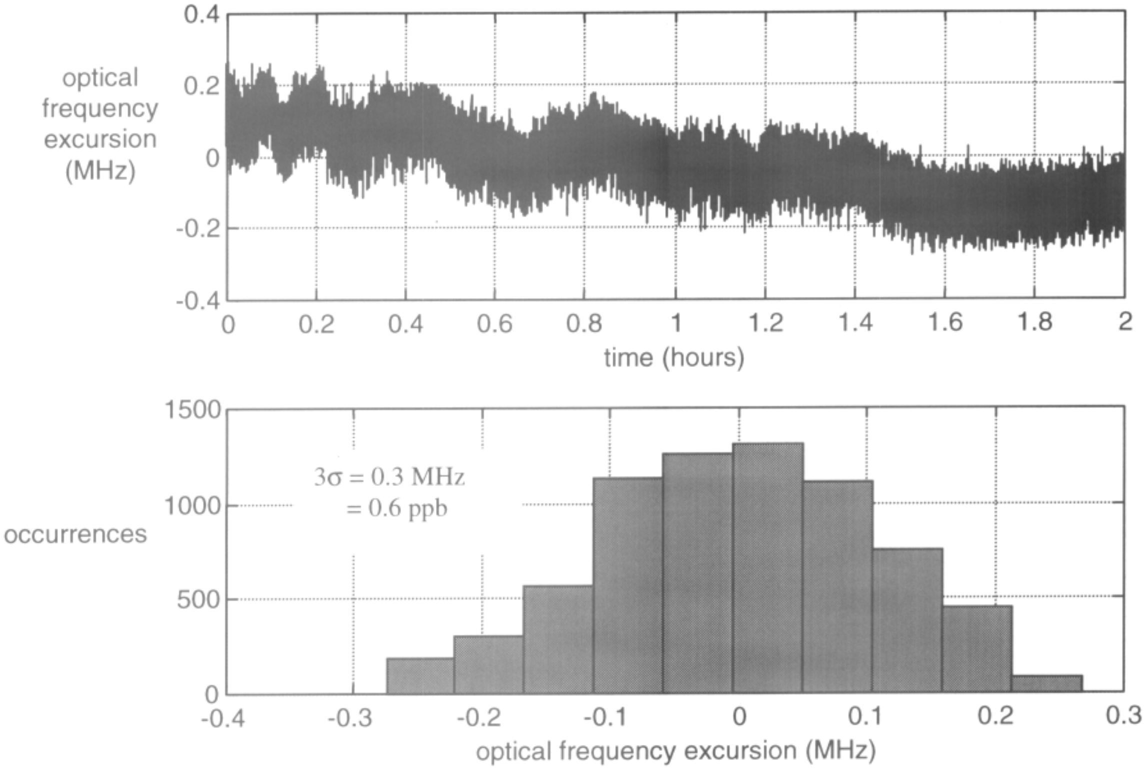


Figure 3 – laser head frequency instability data

Optics

An optical analysis was completed as part of the optical specification procedure. This analysis is based on Jones matrix models of the individual optical components that are assembled into the high-stability plane mirror interferometer configuration. The specifications for the individual components are plugged into the model and a simulation then predicts losses and measurement errors due to beam mixing. Errors due to wavefront distortion and target mirror rotation are also calculated. The analysis shows that if the components meet the specifications, that a 250 μW optical power source will deliver 3 μW to the phase interpolator's fiber optic receivers. It also predicts that the maximum interferometer related errors, not including thermally induced optical path length errors, is less than 20 nm. The temperature coefficient of the high-stability plane mirror interferometer is less than 10 nm/°C. The measurement error resulting from the optics is less than the allotment of 30 nm under the conditions specified in the design overview. All of the optics are miniature (i.e., ½″ polarization beam splitter cube).

Phase Interpolation Electronics Board

The phase interpolator board uses a digital algorithm to interpolate the phase between the measurement signals and the optical phase reference. Preliminary error analysis predicts that the most significant phase measurement error would stem from quantization error and shot noise in the photodiodes of the analog front end. Graphical representation of the two errors showed that quantization error would be the most significant error source at about 8.8 nm. Experiments carried out on the first electronic boards fabricated backup the preliminary analysis. The displacement measurement error resulting from the phase interpolation board is less than the allotment of 40 nm.

Acknowledgements

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References

1) North Carolina Center for Precision Metrology, University of North Carolina at Charlotte, HWY 49 North, Charlotte, NC, 28223.
2) Zygo Corporation, Middlefield, CT, 06455.