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Fiber-Interferometric Sensor for Velocity Measurement in the Planck-Balance

Vitalii Shmagun[1], Thomas Kissinger, Thomas Fröhlich
Institute of Process Measurement and Sensor Technology, Technical University of Ilmenau,
Ehrenbergstraße 29, 98693 Ilmenau, Germany
[1] vitalii.shmagun@tu-ilmenau.de

Summary:

This work describes the use of a compact fiber-interferometric sensor for velocity measurements for the Kibble balance method. Our fiber-interferometric sensor was compared within a Planck-balance setup with a commercial reference interferometer. Results show that the fiber-interferometric sensor is capable of high accuracy velocity measurement comparable with the reference interferometer. High performance and compactness of the sensor head allow it to be integrated into small-size systems, where the use of the conventional interferometer systems is limited or not possible.

Keywords: Interferometer, Kibble Balance, Planck calibration, Velocity Measurement

Introduction

Interferometric displacement measurement plays an important role in force measurement instruments, as it allows non-contact measurement with high accuracy and traceability to the meter definition. Laser interferometers are the primary tool for traceable velocity measurement during the Planck calibration in Kibble balance systems [1], which is the focus of the paper. Interferometers are also used in other precise force measurement instruments, such as calibration stages for characterization of force transducers for dynamic measurements or for calibration of force-displacement curves (spring constant) of AFM cantilevers [2].

Conventional interferometer systems used in the instruments mentioned above are based on helium-neon lasers, which provide very high frequency stability and coherence, but have large size and short lifetime, which is considered being the main drawback of the He-Ne laser in industrial applications. In addition, the complicated optical design of a conventional interferometer leads to precise alignment requirements and limited integration ability due to the large size of the interferometer [3].

With the rapid development of telecommunication technology, more and more semiconductor lasers appear on the market with performance characteristics suitable for interferometry applications. The major advantages of a laser diode are its long lifetime and the possibility to directly modulate the laser frequency by modulating the laser injection current.

Laser frequency modulation allows the use of various modulation techniques [4, 5] in low-finesse Fabry-Perot configurations, avoiding a complex optical interferometer setup, since the second optical quadrature signal for the phase demodulation does not need to be measured directly. Thus, the optical setup may consist of only a compact fiber-coupled collimator as a sensor head, pointing at the measurement surface.

The compact measurement head allows to integrate the interferometer into small-size systems, where the use of a conventional interferometer would be limited.

Fiber-Interferometric Sensor

The basic setup of the fiber-interferometric sensor is shown in Fig. 1. The light from the laser diode passes through the circulator to the fiber-coupled collimator. Part of the light is reflected from the fiber end back to the fiber, forming the reference beam. The transmitted light passes through the collimator lens, is reflected off the mirror and is coupled directly to the fiber. The reflections from the fiber end and the target surface form an interference signal that is fed back through the circulator to a photodetector.

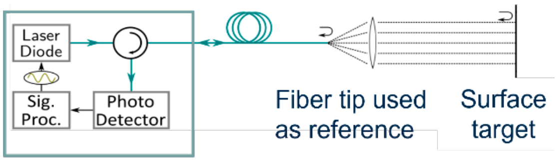

Fig. 1. Basic setup of the fiber-interferometric sensor

To demodulate the phase of the interference signal, a range-resolved interferometry [5] method is used, which allows to distinguish between single-pass and double-pass modes [6] of the fiber interferometric sensor and exhibits high linearity of demodulation.

To ensure traceability to the meter unit, part of the laser output is split with a coupler and directed to a hydrogen cyanide gas cell with a separate photodetector behind it. The offset current of the laser diode is manually adjusted to the center of the gas absorption line using the amplitude of a photodetector signal as feedback.

Velocity Measurement in the Planck-Balance

Our recently developed Planck-Balance (PB2) system [1] is based on the Kibble-Balance principle. In the velocity mode of the balance, the electromagnetic force factor Bl of the coil-magnet system is determined and can then be used in the force mode to calculate the force applied to the coil.

During velocity mode, the coil oscillates in the magnetic field and the coil position x is measured with an interferometer through several complete cycles, simultaneously to the measurement of the induced voltage U with a digital voltmeter. The Bl is then defined as

$$Bl = \frac{U_0}{\omega \cdot x_0}, \qquad (1)$$

where U_0 is the amplitude of the induced voltage in the coil, $\omega = 2\pi f$ and x_0 are the frequency and the amplitude of the coil displacement, respectively. These parameters are usually determined with a sine-fitting algorithm and for PB2 are in the following range $f = 1...10\ \text{Hz}$, $x_0 = 10...40\ \mu\text{m}$.

Experimental Setup

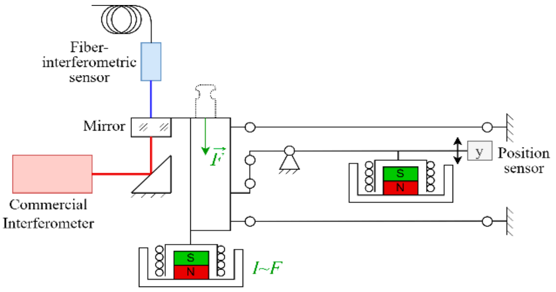

Fig. 2. Planck-balance setup.

The fiber-interferometric sensor was installed in the Planck-Balance setup (Fig. 2) so that the sensor and the commercial interferometer are pointed at the same mirror from opposite sides. It allows to directly compare displacement and velocity measurements taken with a sensor and a commercial interferometer. A multichannel data acquisition unit is used for synchronous data acquisition from both interferometers.

Results

Several measurements were made in which the coil was moved sinusoidally at a frequency of 1 Hz and an amplitude of 20 µm, and the coil position was measured for 10 seconds simultaneously using a commercial interferometer and the fiber interferometer sensor. The velocity amplitude $v = \omega \cdot x_0$ was then estimated with a sine-fitting algorithm for both displacement signals and compared. The comparison shows that the velocity amplitude v_{fiber} obtained with the fiber interferometric sensor has a systematic deviation $\Delta_{sys} = -18$ nm/s from the amplitude v_{int} obtained with the commercial interferometer. The systematic error is believed to be caused mainly by the mechanical misalignment of the sensor and will be the subject of further investigation. Fig. 3 compares the extracted velocity amplitudes for each interferometer type over 6 repeats of the measurement, with the discussed systematic error subtracted from v_{fiber}. The velocity measurements with the fiber interferometric sensor are found to be in very good agreement with the readings of the reference interferometer, with a remaining standard deviation between the two interferometer types of only 0.1 nm/s.

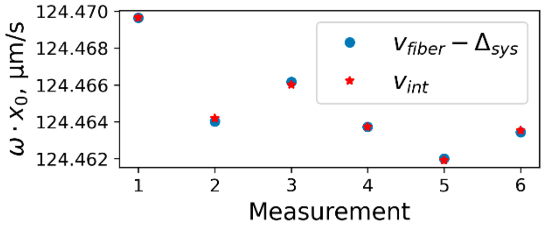

Fig. 3. Calculated velocity amplitude for each measurement.

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