Development of a traceable laser-based displacement calibration system with nanometer accuracy

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Abstract

High precision sensors become increasingly sensitive due to the use of advanced measuring principles and construction techniques. Traceable accuracy though can only be achieved via calibration. Based on a Fabry-Perot interferometer we have developed a calibration set-up for high precision displacement sensors that allows calibrations over a range of 300 μm with an uncertainty of about 0.5 nm. The resolution is smaller than 0.1 nm.

The resonance frequency of the Fabry-Perot cavity is tracked by a slave laser. Its frequency is measured against a standard laser. By using the well known relation between the resonance frequency and the displacement of the cavity mirror the frequency data can be compared with the readout of the sensor which is connected to the moving mirror.

By locking the slave laser to successive resonances of the cavity the calibration range is not limited by the tuning range of the laser.

Keywords: Displacement calibration, Laser measuring instrument

Introduction

A new class of instruments has appeared which has sufficient sensitivity for measurements at nanometer level. Examples are SPM, capacitive and inductive sensors and interferometers. These instruments offer resolution at sub-nanometer level, absolute accuracy though can only be achieved by performing a calibration. Currently the only instruments which have sufficient and traceable accuracy to perform this kind of calibration are X-ray interferometers and laser interferometers, but they are often not practical or accurate enough [1][2].

Also calibrations have been done by directly calibrating sensors against the mirror of a laser using the well known relation between frequency and displacement [3][4]. The problem with these set-ups is the thermal instability of the laser resonator which causes significant drift errors in the calibration.

We have solved the thermal instability problem with the apparatus in Fig. 1.

It is based on a Fabry-Perot cavity to which a laser is frequency-locked. As one of the mirrors of the cavity is displaced, the laser tracks the change in resonance frequency of the cavity. At the same time a sensor to be calibrated is connected to the mirror. A comparison of the sensor readout with the frequency data defines a calibration.

This calibration set-up is designed to give sub-nanometer resolution and an accuracy at nanometer level.

The optical layout

Essential to the set-up is the F-P cavity consisting of two mirrors with a radius of 60 cm and a resonator length of 140 mm. The mirrors have a reflectivity of 0.99. The resonance frequency, \( f \), of the F-P cavity is described by:

\[
 f = \frac{k_c}{2Ln}.
\]

In this equation \( k \) is the mode number, \( c \) is the speed of light, \( L \) the resonator length and \( n \) the refractive index of the medium inside the resonator.

If one of the mirrors is displaced the resonator length will change by \( dL \) which gives a frequency change \( df \) according to (1) of:

\[
 \frac{dL}{L} = -\frac{df}{f}.
\]

As the resonance frequency changes, a control loop keeps the slave laser frequency locked on this resonance. Feedback for the control loop comes from modulating the frequency of the slave laser and phase sensitive detection of the first harmonic of the reflected signal from the F-P cavity.
An avalanche photodiode connected to a counter registers the beat resulting from mixing the reference and slave frequencies. The frequency change $df$ converts into displacement data $dL$ with eq. (2) and is compared with the readout of the sensor undergoing calibration. This sensor is directly connected to the moving mirror of the F-P cavity. The slave laser is of the open cavity type, having a 105 mm cavity length. This enables a tuning range of 1250 MHz. The laser tube of the slave laser is filled with the $^{22}\text{Ne}$-isotope because the Doppler profile of this isotope is shifted by 800 MHz in relation to the normal $^{20}\text{Ne}$-isotope. In this way the beat signal between slave laser and standard laser can be unambiguously determined.

From eq. (2) one can see that for an absolute laser frequency of $4.74 \times 10^{14}$ Hz, a F-P resonator length of 0.14 m and a tuning range of 1250 MHz a displacement of only 370 nm can be tracked by the slave laser. For measuring larger displacements consecutive modes must be tracked. This means that the slave laser tracks one mode for 316 nm, then it is unlocked from this mode and shifted about 1070 MHz in frequency so that it can be locked to the next mode. By repeating this locking/unlocking procedure the F-P cavity is tracked over a calibration range of hundreds of micrometers.

From eq. (2) it can also be seen that the ratio of frequency change to length change of the resonator is $3.39 \times 10^{15}$ Hz/m. This fact combined with an accuracy in frequency measurement of 10 kHz gives a theoretical resolution of less than 0.01 nm. In practice the resolution is limited by the stability of the mechanical set up, the refractive index stability and the locking stability. This results in a practical resolution of a few hundredths of a nanometer.

For maximum traceability, the measured displacement must be traced to the standard of length as directly as possible. In this case the standard laser, which is an iodine stabilised He-Ne laser, and the sensor undergoing calibration are connected by only two elements i.e. the F-P cavity and the frequency measurement.

The mechanical layout

In Fig. 2 the layout of the F-P interferometer is shown. The F-P cavity is mounted on a frame which also holds the slave laser. In order to match the laser beam to the TEM00 resonance mode of the cavity the slave laser and cavity can be adjusted. For this reason a mode matching lens is also mounted [6].

The cavity itself is contained in an isolating box which minimises temperature fluctuations and acoustic vibrations from the environment. The frame is placed on a vibration isolated table. The layout of the cavity itself is shown in Fig. 3.

The sensor under calibration is positioned on the calibration platform. Through a hole in the middle of this platform the moving mirror can be accessed. The mirror is mounted in a guiding mechanism that consists of 2 parallel leafsprings. This mechanisms enables linear translation with only sub-arcsecond parasitic rotations. The mechanism can be driven directly by a piezo, for calibrations over a small range of 10 μm. or through a lever by a piezo screw for calibrations over a range of 300 μm (not shown).

Experimental results

While the above described cavity design is under construction tests have been done with a similar cavity, originally used as a measuring laser [4]. Fig. 4 shows the result of a stability test over 7 hrs.
Fig. 4 Drift of the F-P cavity.

Initially there was some drift because the isolating box had just been closed. After about one hour the temperature inside the box had stabilised enough to keep drift levels well below 1 nm/hr. The effect of the change of refractive index was compensated for with an uncertainty of \(dn < 2 \times 10^{-8}\).

Fig. 5 Linearity error of a heterodyne interferometer.

Fig. 5 shows the residue of a calibration of a heterodyne laser interferometer. Due to the non perfect polarisation splitting of the two orthogonally polarised beams there is a sinusoidal linearity error [7]. Because of the double pass interferometer used, the period of this error is 158.2 nm. The amplitude of the error is only 3 nm but can clearly be distinguished. The set-up used for the tests was not optimised. This meant that the tuning range of the slave laser was not large enough for tracking the F-P cavity used over 100 % of its range. Therefore only a part of the sinusoidal deviation in Fig. 5 could be measured.

The same effect occurs in the curve of Fig. 6. It shows the residue of a calibration of an inductive probe after fitting it with a first order curve. Over a range of more then 2000 nm the width of the curve is about 4 nm caused by the noise in the probe electronics. Also there is a nonlinearity with an amplitude of 2 nm.

Uncertainty analysis

As has already been mentioned in the previous text, the F-P cavity offers sub-nanometer resolution due to its high frequency to displacement ratio. The accuracy is limited though by the following factors:

- The frequency measurement is accurate to about 10 kHz. This causes an uncertainty in the calibration of about 0.01 nm.
- The locking stability of the slave laser to the F-P cavity is limited by the noise in the electronics. Because of the high intensity of the optical signals used for locking, the S/N-ratio is high and therefore the effect of noise is smaller then 0.01 nm.
- Parasitic rotations of the moving mirror cause an uncertainty in the measurement of 0.01 nm.
- Non perfect alignment of the displacement axes of the moving mirror and the sensor cause a cosine error which amounts to an uncertainty of 0.1 nm.
- Because the cavity is not completely evacuated there is still some uncompensated effect of the refractive index of air. The uncertainty caused by this effect is 0.15 nm. By measuring air temperature, air pressure and humidity it is possible to virtually eliminate this uncertainty.
- The limited thermomechanical stability of the construction introduces an uncertainty of at most 0.5 nm during a calibration of 15 minutes.

These factors together result in a total uncertainty of a calibration of 0.53 nm.

Obviously the most significant contribution to the total accuracy is made by the thermomechanical stability of the F-P cavity. This is in turn mainly caused by the bending of the calibration platform due to (very small) temperature gradients. The new design will partly eliminate this effect.

Conclusion

The design for a F-P interferometer described in this paper enables calibrations over 300 \(\mu\)m with an uncertainty of 0.5 nm and a resolution smaller than 0.1 nm.

The calibration range is not limited by the tuning range of the slave laser because successive modes of the F-P cavity are being tracked.

The measurements are traceable due to the incorporation of the standard laser into the measurement set-up.

Literature


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