Publishable JRP Summary Report for JRP SIB08 subnano
Traceability of sub-nm length measurements

Background

Although a sub-nm uncertainty of a measured length or displacement appears to be rather small and one tends to think it may be negligible, there are already important applications in metrology and industry where accuracies in this range are needed or will be needed in the very near future. It is therefore necessary for national metrology institutes to address this issue.

Need for the project

Today, accurate measurements of displacements or the dimensions of macroscopic bodies are usually made with optical interferometers that measure the sought quantity in terms of the wavelength of light. The wavelength λ of an electromagnetic plane wave, that is an infinitely extended wave with plane parallel wavefronts, is related to its frequency f via the speed of light c in the respective medium by $\lambda = c\ /\ f$. Therefore, by knowing the exact frequency of a laser and the speed of light, which depends on the medium's refractive index, a wavelength can be calculated. However, this wavelength is only an approximation to the *real* wavelength. The wavefronts in real interferometers are curved and never infinitely extended. Although the plane wave approximation can be quite good in some cases, real wavelengths differ typically by parts per million up to parts per thousand depending on the wavefront curvature and position in relation to the light source. This means, for a wavelength in the visible light region (between 380 nm and 780 nm), the real wavelength differences can reach picometre level. In order to measure displacements or lengths with sub-nm accuracy, theoretical models which consider the actual shape of the wavefront must be used to calculate a correction to a measured value. Up to now, appropriate models are neither readily available nor validated.

Another class of devices widely used to measure displacements are capacitive sensors. The measurement principle is based on the capacitance of a plate capacitor. By knowing the area of the electrodes, the permittivity of the medium between the electrodes and by measuring the capacitance in principle one can calculate the distance between the electrodes. However, the precision of such a measurement (the number of digits which can repeatedly be resolved) can be much better than the accuracy (small deviation from the real value) of the quantities needed to calculate the absolute distance. Therefore, although the precision is very high, accurate measurements depend on calibration and may drift in time and change with environmental conditions like humidity and temperature.

Scientific and technical objectives

The purpose of this JRP is to enable traceable measurements in the sub-nm range for optical interferometers as well as improved capacitive sensors. Traceability of sub-nm length measurements requires consistent modelling of the measurement system as well as cross validation between different measurement principles. For this purpose the measurements have to be improved regarding uncertainty, resolution and dynamic range of displacement. Models for the propagation of aberrated wavefronts in optical interferometers as well as a model based correction of alignment errors and environmental effects of capacitive sensors and a traceable wavefront sensor with an uncertainty better than $\lambda/30$ and only limited by its repeatability will be developed. The influence of roughness and drift in optical interferometers will be investigated which will result in improved uncertainty budgets. The FPI displacement measurement and related sensor calibration will be improved to sub-nm uncertainty by means of a detailed uncertainty budget,

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with particular attention for environmental effects, sensor referencing, alignment, noise and drift of the FPI. The target uncertainty for an existing metrological FPI is sub-nm for a displacement stroke of 1 µm and 10 nm for a stroke of 100 µm. A proper sensor calibration methodology using the FPI and supporting sub-nm uncertainty, specifically investigated for selected capacitive sensors has to be found. A picometer-range uncertainty for the FPI is targeted by means of improved ambient stability, referencing compatibility and optical frequency comb traceability to the time standard. Target uncertainty is 10 pm for a displacement stroke of 1 µm. Quantised positioning of x-ray interferometer (XRI) measurements with a resolution of 24 pm, quadrature counting of x-ray fringes and scanning ranges up to 10 mm will be enabled. An improved sensor design for capacitive sensors with lower sensitivity to alignment and environment effects will be developed. Alignment errors in the arcmin region and environment effects on capacitive sensors by referencing to optical interferometers and XRI will be analyzed. The requirements for a displacement transfer standard will be specified and the available technology will be reviewed. Eventually, a prototype of a displacement transfer standard facilitating cross-validation of at least 2 different types of interferometers with sub-nm uncertainty [10 pm (1 nm) for a stroke of 1 µm (100 µm)] will be suggested by a feasibility study.

Expected results and potential impact

Software that models the propagation of experimentally detected laser-beam wavefronts will be developed. Therefore, accurate measurement of wavefronts is a premise which is addressed by the development of a flexible and traceable wavefront sensor. A combined optical and x-ray interferometer set-up is then used to validate the theoretical prediction for the optical displacement measurement. For the capacitive sensors new technological methods as well as the influence of environmental effects on the reproducibility are studied in direct comparison to sophisticated Fabry-Pérot (FPI) and x-ray (XRI) interferometers. The scientific and technological output is also evaluated in a feasibility study about a transfer standard for length measurements with sub-nm traceability.

The following results have been achieved so far:

<u>Investigation of capacitive sensors using optical interferometry and x-ray interferometry</u>

Commercial off-the-shelf capacitive sensors were selected and made available for investigation by collaborating partners from industry. Furthermore, design specifications of a custom self-aligning capacitive sensor concept from TU Delft were further iterated. For these various sensors, appropriate mounting, alignment and referencing methodology has been developed and necessary instrumental modifications of the interferometers for hosting the capacitive sensors together with appropriate reference target electrodes have been performed. The VSL Metrological FPI was supplied with a more robust frequency stabilisation scheme of the measurement laser, improved ambient shielding and additional capacitive alignment sensors. System performance and sensor calibration methodology are under investigation with a current emphasis on noise and drift properties, see SPIE Proceedings 9203, 920308 (2014). Further investigation is addressing the performance of the self aligning capacitance sensor system.

Designs of holders for both the self aligning capacitance sensors and the conventional sensors are in progress and the stability of commercial slip-stick stages that form part of the alignment mechanism is being investigated. NPL and TU Delft collaborated with PI, the supplier of the self-aligning sensor to plan strategy and a modified sensor design. A study has been made of the dimensional stability of the stages used for mounting the sensors.

A paper "Highly-stable Electronic Sensor Interface for Capacitive Position Measurement" was prepared and accepted for publication in KEM (Key Engineering Materials) journal. During a working visit to TU Delft, issues for sensor mounting and transfer standard were discussed. The design of the electronics for Interface 1 was completed. Due to an error in the electrical schematics, the PCB layout design was restarted and delayed. For this reason, the production of Interface 1 was delayed and the tests for performance were postponed to end of March 2014. A paper for I2MTC 2014 conference about the design of the interface electronics was prepared and accepted for publication.

The electronics for the sensor interface was completed. Tests for initial accuracy, noise, temperature- and long term stability were performed in TU Delft. Two devices of the sensor interface electronics were sent to VSL and NPL, respectively. During working visits, VSL and NPL partners were trained in TU Delft to work with the interface. A paper for IMEKO TC4 2014 conference about the improvements of the interface electronics and the achieved experimental results was prepared and presented.

The TUBITAK differential Fabry-Perot interferometric system has been redesigned and improved for displacement measurements in the range from 10 pm to 10 µm (or more). In the range from 10 pm to 1 µm the standard measurement technique presented in the EMRP Nanotrace Project is used. For the range from 1 µm to 10 µm (or more) the novel method that combines the Fabry–Perot resonance counting technique and the beat measurement technique is introduced. For the displacements over 1 µm, an opto-electronical system simulating the X-ray interferometer and capacitive sensor movements has been developed together with its control program. As a result displacement measurements in the range from 1 µm to 10 µm (or more) have been performed with an uncertainty ≤ 3 nm.

Modelling of optical interferometers

Based on rigorous vectorial diffraction theory the vectorial ray-based diffraction integral (VRBDI) method has been established. This will be be published soon.

The simulation software for the Monte Carlo modelling of errors in homodyne interferometer fringe interpolation was developed and the preliminary results containing empirical sensitivity coefficients for error contributions are available.

Wavefront measurement

A two dimensional version of the Traceable Multiple Sensor (TMS) principle has been developed. Four different solutions for separating systematic errors of the wavefront sensor from errors of the (unknown) calibration wavefront have been developed. These error separation techniques are based on shifts and/or rotations of the wavefront sensor relative to the wavefront under test.

An experimental set up for wave front sensor calibration has been realized and tested.

Key element is a Shack Hartmann wavefront sensor, consisting of a CCD camera together with an array of microlenses. Each of the microlenses acts as an independent sensor and has to be calibrated by itself. The TMS method is most suitable for this purpose. For this calibration scheme the wavefront sensor has to be moved stepwise across a homogeneous plane reference wave. The position as well as the tilt of the sensor during the scan has to be known precisely. The reference wave is generated by two different laser sources (λ=532 nm and λ=633nm) which are optionally coupled into a single mode fiber. The end of the fiber is placed into the focal point of a long focal length mirror collimator to generate a nearly plane wave of 100 mm diameter. The quality of the mirror and therefore the quality of the wavefront has been checked interferometrically by a Fizeau interferometer. The angular orientation of the sensor during the scan is detected using an autocollimator and a calibrated flat mirror which is mounted close to the sensor. Hence sensor and mirror are moved simultaneously. The mirror was glued into a special designed mirror holder and attached to the translation stage. Knowledge of the topography of the mirror is essential for the error budget of the system. Therefore the topography of the mounted mirror has been measured interferometrically. By mounting an additional mirror and a second autocollimator temporarily the concept for angle correction has been tested successfully. Furthermore the positioning accuracy was verified using a length measuring interferometer. First measurements regarding repeatability and reproducibility of the Shack-Hartmann sensor were performed.

The control program has been developed further and the evaluation program is ready for use. A paper about the reference free calibration method for flats and wavefronts has been submitted to Optics Letters (tilte: “Absolute Flatness Measurement Using Two Flats Based on Relative Movements and Tilt Measurements”). Furthermore, PTB applied for a patent for the reference free calibration setup. The calibration procedure has been performed several times within a period of more than 3 month. The systematic sensor error as well as the topography of the reference wave front has been determined under various conditions. Allowing for an independent measurement of the reference wave a pentaprism was mounted onto the translation stage, too. Thus a part of the beam is deviated by a constant of 90° independent from a tilt of the stage, and by determination of the center of mass of the beam during the scan, the profile can be reconstructed. It was found that the corresponding cross sections differ no more than 16 nm (PV) compared to each other. Furthermore various optical elements were included into the set up to modify the optical path length of the reference wave front in a known way. For comparison their effect was measured using a Fizeau interferometer.

Firstly a precision optical glass was mounted fix to the wave front sensor to modify the systematic sensor error. From theory as well as from the interferometrical measurement a contribution to the systematic sensor error regarding defocus and astigmatisms (2, 2) is expected. The results of the calibration procedure differs no more than 2 nm for the corresponding Zernike coefficients.

Furthermore a high quality optical flat was inserted into the reference beam which reduces the originally existing wave front curvature as well as pieces of an overhead transparency which in contrast strongly distort the wave front. The results from the optical flat are in good agreement with the expected results from the interferometrical measurement (deviation of 30 nm (PV) over the beam with a diameter of 70 mm). A quantitative comparison for the overhead transparency was not possible, because the Fizeau interferometer could not deal with its steep phase gradients but the calibration procedure could be carried out und thus the determination of the systematic sensor error was possible.

In conclusion we found for the systematic senor error a repeatability of 6 nm for consecutive measurements. For calibration procedures using identical reference wave fronts the deviation from the mean was no more than 8 nm and taking different realizations of the reference wave front into account (incl. optical flat and overhead transparencies) the deviation from the mean did not exceed 15 nm corresponding $<\lambda/30$ (PV).

Besides the determination of the systematic senor error, the associated uncertainty of the systematic sensor error for the cooled Shack-Hartmann wavefront sensor has been performed. For this the mechanical stability of the setup as well as the mechanical stability of the sensor and its behavior when changing the operating temperature was investigated. The calibration procedure and the evaluation of the data were performed several times and under various conditions e.g. for different shapes of the reference beam and for different reconstruction parameters. In addition a recalibration was performed after the sensor was used elsewhere.

Calibration of the wavefront sensor based on shear interferometry which was developed by BIAS had been prepared. Modifications to the mounting of the calibration setup were carried out prior to calibration. The light power was not sufficient and a modification of the light source was also needed. The measuring and control program as well as the evaluation algorithm were adapted to the parameters of the sensor. Investigations of the sensor stability and a first execution of the calibration procedure have been performed.

<u>Validation of the modelling by XRI and optical interferometry</u>

Assembly of the XRI and other components of the vacuum vessel is close to completion. The methodology to validate the optical simulation software has been refined to operate only the primary optical interferometer for several input beams with different beam parameters and compare the Si-28 lattice constant, measured in terms of effective wavelength, with simulated results.

<u>Development of double ended gauge block interferometry</u>

Optics and data acquisition of a double ended gauge block interferometer have been redesigned and acquired for needs of the phase stepping method. A phase stepping algorithm and software has been applied to the double ended interferometer and the surface topography analysis has been further improved. Procedure for systematic wavefront error correction was planned, implemented and tested. Slave and cross methods were selected for phase change correction study. A first round of test measurements for determination of phase correction has been carried out and analysed. A second set of test measurements is under preparation. MIKES is taking part to EURAMETproject #1272 “Phase correction for interferometric measurement of gauge blocks” with CMI and GUM for comparison of phase correction determination. The results of the DEWLI development were presented in Macroscale 2014 conference.

<u>Measurement devices technology</u>

Software has been written for a dual self actuating capacitance sensor and drift measurements have been started prior to a comparison against the XRI.

Several concepts for improved actuation of the x-ray interferometer have been developed. These include a dual actuator with capacitance sensors which did not perform satisfactorily due to excessive noise and drift in the commercial sensor electronics. A new single point actuator has been developed and a first version of a low noise power supply for the pzt as been tested. Some modifications will be made to acomodate higher capacitance pzt actuators.

Initial routines for quadrature detection of the x-ray interferometer signals have been written.

A new prototype FPI scheme (dubbed pmFPI) is under development at VSL, aiming for picometer-level measurement uncertainty. A short (< 0.5 mm long) high-finesse optical cavity was chosen for limiting the prohibitive air refractive index fluctuations under practical ambient measurement conditions. The compact, small-sized optical bench will also facilitate thermo-mechanical stability and shielding. Traceability has been established by means of a (portable) bench wavemeter rather than the more fragile and costly iodine stabilised standard laser as is necessary for the larger MetFPI. Experimental investigation has indicated the scaling of air refractive index fluctuations down to about 10 pm equivalent for relative displacement measurements with the pmFPI optical test bench. The selected instrumental components show targeted performance with a high cavity Finesse, i.e. 13 MHz FWHM resonance linewidth, as is required for referencing to the wavemeter with similar resolution, equivalent to approximately 10 pm displacement.

Impact

Project meetings are regularly held every half year. The most recent meeting was linked with the Macroscale 2014 conference this October in Vienna. The meeting was open for interested stakeholders. Several presentations have been given at conferences and during visits of stakeholders and companies. ISO/TC213 visited MIKES 20 Sept 2013. The Subnano project and double ended interferometry were introduced to visitors. Double ended gauge block interferometry was discussed within CCL DG1 Gauge Blocks. Further information can be found on the project web site at http://www.ptb.de/emrp/subnano.html.

The project aims to develop improved traceability of dimensional nanometrology in high end instrumentation used at NMIs and in high tech industries. Applications include e.g. metrology for the semiconductor fabrication and lithography, and nanopositioning industries as well as other industries with challenging requirements such as the space instrumentation industry that requires a one-off calibration that must be valid for the lifetime of the instrument. Cutting edge NMI metrology projects, e.g. the re-definition of the kilogram, will benefit from this project. The results will lead to standardised, traceable and validated measurement methods for calibrating precision instruments; will enhance the quality assurance of national metrology institutes, the calibrations they perform for customers and will improve ultimate quality of the products manufactured in Europe, thereby enhancing the competitiveness of European industry. Precision engineering is an important technology for the manufacturing of medical equipment especially in the nano medicine. Therefore advancements in these fields could have impact on medical technology leading to better healthcare. Improved accuracy in manufacturing could potentially lead to more efficient production thereby reducing waste and energy consumption. Further social benefits may emerge from impact of improved uncertainties in production engineering providing new information technology components and consumer electronics.

TUBITAK's Differential Fabry-Perot Interferometer (DFPI) has been applied to detection of very small angles in the scope of another EMRP project (SIB58 Angles – Angle Metrology). During application, down to 1 nrad angular steps were generated using TUBITAK's High Precision Angle Generator and these steps were detected using the TUBITAK DFPI and frequency stabilised lasers as an alternative and outperforming method to conventional angle interferometers. The TUBITAK DFPI sensed the displacement measurements (further angular displacements through optical configuration) with picometer sensitivity free from linearity errors. The small angles with nrad sensitivities are in high demand for use in precise angle metrology application areas. It is expected that the knowledge produced will be of benefit to the synchrotrons & XFEL community, gamma ray spectroscopy applications, fundamental physics, and scientific space missions as well as NMIs and angle measurement device manufacturers.

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