21st International Research/Expert Conference
"Trends in the Development of Machinery and Associated Technology"
TMT 2018, Karlovy Vary, Czech Republic, 18th – 22nd September, 2018

TRACEABILITY OF INDUSTRIAL MEASUREMENTS WITH LASER INTERFEROMETERS

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ABSTRACT
Laser interferometers are often used instruments for accurate one-dimensional measurements in precise industries like automotive industry, lithography, and nanotechnology, as well as in calibration laboratories. In metrology laboratories and in clean rooms with advanced environmental conditions control, accuracies of few nanometers per meter can be reached. In order to be able to reach such accuracies, laser interferometers and corresponding sensors for measuring environmental conditions shall be calibrated periodically. There are two common methods available: calibration of laser frequency by using primary length standards, and comparative calibration with a reference laser interferometer. While the first method is appropriate for high-level metrology laboratories with very high precision demands, the second is more "user friendly" and is convenient for accredited laboratories and industry. Laboratory for Production Measurement at the Faculty of Mechanical Engineering in Maribor has quite long experiences in applying the first, more scientific, method, while the procedure based on the second method is currently being developed and tested. This article is presenting basic approaches of assuring traceability of measurements with laser interferometers, as well as the advantages and disadvantages of both commonly used calibration methods as regards measurement uncertainty, as well as the form and application of the calibration results.
Keywords: laser interferometer, traceability, uncertainty of measurement

1. INTRODUCTION
Traceability of industrial measurements is the most important pre-condition for assuring comparable measurements of a proper quality. Traceability is defined as a link between the measurement and the definition of a unit through an unbroken chain of calibrations. In length metrology, laser interferometers (LI) are very high level of measurement standards. They can be used as instruments for direct displacement measurements in precise industries like automotive industry, lithography, and nanotechnology, or as standards for calibrating very accurate 1D, 2D and 3D measurement instruments in metrology laboratories, as well as in a shop floor [1, 2].
In order to be able to reach expected accuracy, laser interferometers and corresponding sensors for measuring environmental conditions shall be calibrated periodically. There are two common methods available: calibration of laser frequency by using primary length standards, and comparative calibration with a reference LI. While the first method is appropriate for high-level metrology laboratories with very high precision demands, the second is more "user friendly" and is convenient for accredited laboratories and industry. The most important advantage of the second method for end users is in providing calibration results for the complete measurement system (laser, optics, counter, and sensors). When applying the first method, the end user gets separate calibration certificates for the laser frequency and for sensors. The user shall be capable to evaluate the influence of different systematic errors and measurement uncertainties on the final LI result. Laboratory for Production Measurement at the Faculty of Mechanical Engineering in Maribor has quite long experiences in applying the first, more scientific method, while the procedure based on the second method is currently being developed and tested.

2. CALIBRATION METHODS AND TRACEABILITY CHAINS

As already mentioned in the introduction, there are two commonly used methods for calibrating LIs. Calibration of the laser frequency provides the user with direct traceability to the primary frequency standard. However, in order to calculate the wavelength (basic increment for measuring length) in real environmental conditions, the LI user shall be able to measure temperature, humidity and pressure with appropriate accuracy. Therefore, the sensors for measuring environmental conditions shall be calibrated separately. Three additional traceability chains to the primary standards of temperature, pressure and humidity must be assured by the end user of a LI. In contrary, the comparative calibration with a reference LI requires form the end user of a LI to assure single traceability chain for the complete measurement system. All other traceability tasks are carried out by the accredited calibration laboratory.

2.1. Calibration of laser frequency with a primary frequency standard

A frequency stabilized laser source is used as a frequency reference for measuring optical frequencies of a laser under calibration by using the beat detection scheme (Figure 1). The reference beam is directed through the beam splitter to the counter. The beam of the laser under test is directed to the beam splitter and there approximately half of it is reflected toward the optical counter, too. The beams are coaxially aligned on long-distance screen by fine adjustment of the mirrors. The beat frequency of the interfered components is then detected by Allan Variance Meter (AVM) [3].

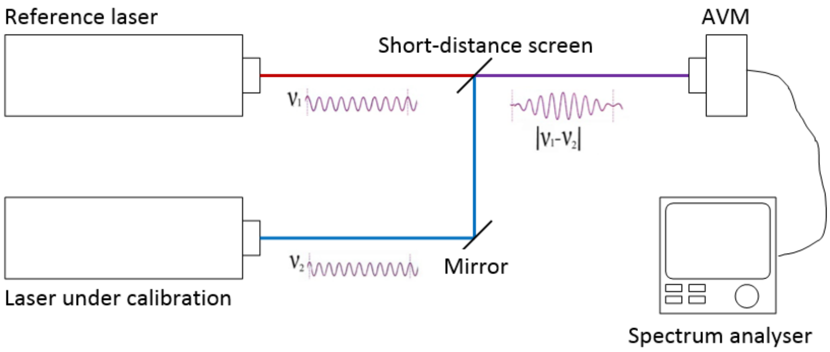

Figure 1. Principle of optical beat measurement.

The calibration system in the Laboratory for Production Measurement (Figure 2) is applied for the definition of a real value of the laser radiation frequency/wavelength and investigation of stability and reproducibility of the laser radiation in the HeNe laser interferometers (with stable red light of nominal vacuum wavelength in the range from 632.990 to 632.992 nm). The system was developed by the company Lasertex in cooperation with the Institute of Telecommunications and Acoustics, Wroclaw University of Technology [4].

Figure 2. Calibration set-up for laser frequency calibration in the Laboratory for Production Measurement

2.2. Comparative calibration with a reference LI

This method is used for calibrating the complete laser interferometer measurement system by comparing results of displacement measurements. The same displacement that is generated on a long stage is measured with the reference LI and with a LI under calibration at the same time (Figure 3). Final displacement results given by both systems, are compared. The "final results" are considering all corrections based on the environmental measurements and built-in compensation algorithms [5].

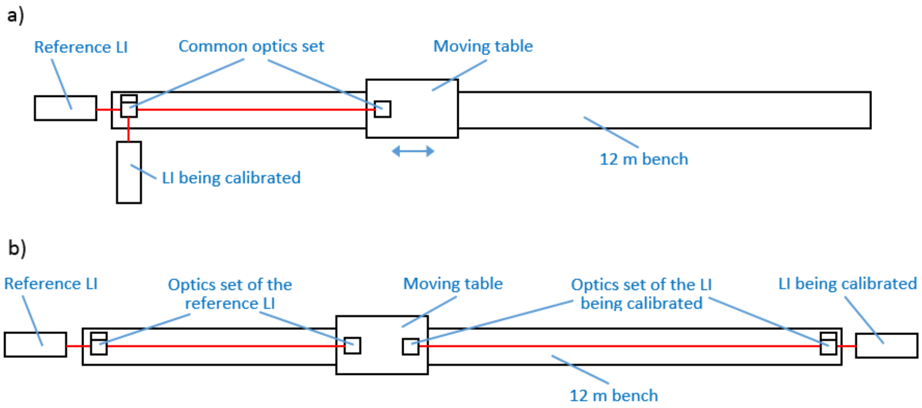

Figure 3. Calibration set-up for comparative calibration of laser interferometers.

Figure 3 is showing two different set-ups that have been investigated in the presented research. Set-up a) uses one common optics set and the beams of both lasers travel along the same path. The advantage of this set-up is in having equal environmental conditions for both lasers. It gives us minimum influence of environmental conditions on the final result. A disadvantage is in a possible interference of both laser beams and in exclusion of the environmental measurement systems from the calibration.
Set-up b) uses 2 optics sets and both environmental measurements systems (the one of the reference LI and the one of the LI under calibration). The disadvantage of this set-up is demonstrated through instable environmental conditions in the room, which are influencing the repeatability of the calibration results, while the advantage is in independent measurement paths with no possibility of interference and in involving measurement and correction of the environmental parameters.

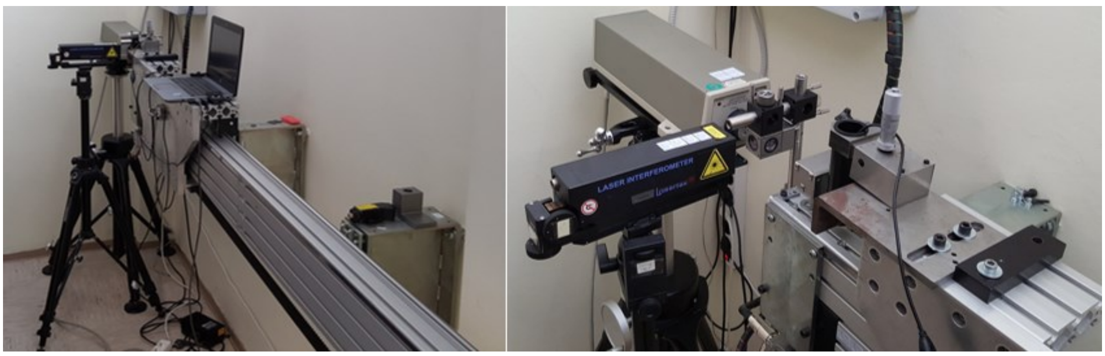

Figure 4. Calibration set-up for comparative calibration of laser interferometers in the Laboratory for Production Measurement.

3. MEASUREMENT UNCERTAINTY

The measurement uncertainty [6] in 2.1. in alibration of laser frequency with a primary frequency standard depends on the stability of the reference laser frequency, accuracy of the AVM counter, sampling period, and on the stability of the laser under calibration. Published calibration and measurement capability (CMC), expressed as relative expanded uncertainty is $U_{rel} = 10^{-9}$.

Contributions to the measurement uncertainty [6] for the comparative LI calibration are listed in Table 1. Very important contributions are homogeneity and stability of the air conditions.

Table 1. Contributions to the measurement uncertainty in comparative LI calibration.

Value	Symbol	Type
Reference LI indication	L_r	Systematic (B)
Indication of the LI under calibration	L_i	Systematic (B)
Stability of the air temperature	T	Random (A)
Stability of the air pressure	p	Random (A)
Homogeneity of the air temperature	T	Random (A)
Homogeneity of the air pressure	p	Random (A)
Air sensor indication	p, T, H	Systematic (B)
Stage guides straightness	s_z, s_y	Systematic (B)

In the current stage of the research it is estimated to be able to reach the total expanded uncertainty of $U = 5$ nm + $10^{-7} \cdot L$ in our laboratory, when calibrating high-quality laser interferometers.

4. CONCLUSIONS

The initial research in the field of calibrating lasers in the Laboratory for Production Measurement was focused in the highest traceability level, since we are acting as the national laboratory for length in Slovenia. The best metrological capabilities (CMCs) in this area were published in the KCDB database at BIPM in 2011. However, an increasing number of LI users is looking for a simple calibration, which could give them a direct information on the systematic error and the measurement uncertainty of their LI measurement system. Therefore, we have developed a measurement set-up for comparative calibration in our laboratory few years ago. Intensive research on the capabilities of this set-up is going on lately in order to establish a reliable procedure, which will be ready for accreditation in near future. Preliminary results are presented in this article, but they still need to be confirmed through numerous test calibrations of different types of laser interferometers.

5. ACKNOWLEDGEMENTS

The authors acknowledge the financial support from the Slovenian Research Agency (research core funding No. P2-0190), as well as from Metrology Institute of the Republic of Slovenia (funding of national standard of length; contract No. C3212-10-000072).

6. REFERENCES

[1] Byman V., Jaakkola T., Palosuo I., Lassila A.: High accuracy step gauge interferometer, Measurement Science and Technology, Vol. 29, 2018.,

[2] Ačko B., Milfelner M.: Temperature-Invariant Material Standard For Monitoring Performance of Machine Tools, 18th International Research/Expert Conference TMT, Budapest, Hungary, 2014.,

[3] Bošnjaković A., Bašić H.: The Method Of Calibration Of He-Ne Laser Using The Npl Iodine Stabilized He-Ne Laser With Wavelength At 633 nm, 18th International Research/Expert Conference TMT, Budapest, Hungary, 2014.,

[4] Budzyn G., Dudzik G., Rzepka J.: Portable digitally controlled iodine stabilized He-Ne laser with very long lock-up time, ICTON Mediterranean Winter Conference, Tunisia, 2007.,

[5] Jaeger G.: Limitations of precision length measurements based on interferometers, Measurement, Vol. 43, I 5, 652-658, 2010.,

[6] EA-4/02: Evaluation of the uncertainty of measurement in calibration, European Accreditation, 2013.