Direct measurement of stationary objects' dimensions with Michelson type incremental laser interferometer

T Stejskal¹, M Dovica¹, S Őuriš², Z Őurišová¹, J Palenčár²

¹ Technical University of Košice, Faculty of Mechanical Engineering, Slovakia
² Faculty of Mechanical Engineering, Slovak University of Technology, Bratislava, Slovakia
³ Slovak Institute of Metrology, Bratislava, Slovakia

E-mail: miroslav.dovica@tuke.sk

Abstract. The paper deals with a design of an original length measuring equipment for a measurement by Michelson-type laser interferometer. Laser measuring operate on the principle of relative movement of two components, where one component is fitted with an interference unit and the other one with a reflector. Such system is capable of measuring the length of displacement post motion, however, it is unable to measure the length of a stationary object. Functionality of the measuring equipment is ensured by a measuring board and a ruler. At a relatively low additional cost, the measuring configuration is capable of measuring the lengths of motionless objects achieving the precision of laser. The paper describes the measurement methodology verified in an experiment. Expanding verification tests of the device may facilitate possible commercial production of such auxiliary device for the Michelson-type laser interferometer, which would make the symposium motto "The future glimmers long before it comes to be" sound especially true.

1. Introduction

The laser interferometer is structurally adapted to measure the positioning accuracy of coordinate systems. The coordinate system comprises a moving part in the form of a guideway in either of the axes. The positions are programmable and the laser interferometer can verify the degree to which the programmed value has been reached [1]. Should the coordinate system lack its own measuring ruler, even then the movement of the moving part can be measured accurately.

The solution is based on a two-carrier measuring equipment for interferometer components. The carriers have a fixed arm with a three-point contact for the rulers, a spot for fitting the interferometer and the reflector, respectively. The carriers can move freely along the ruler and their function is to limit the contact of the arm with the object measured. At the end of both arms, co-linear contact sensors are placed, facing each other. All other movements related to handling the object in preparation for the measurement are performed by the object. This ensures high accuracy and reliability of measurement.

To verify the measurement methodology, a granite surface plate and a precise knife straight edge were used. The carriers and the arms were made of balsa wood. A high accuracy digital sensor was subject to verification as it served as a contact sensor.

Length measurement is principally done in many ways, ranging from utilizing mechanical systems to laser metering. The authors are not aware of any commercial application using the proposed principle.
of measurement linked to Michelson-type laser interferometer. The experiments below confirm that this system could expand the portfolio of measuring products produced and sold by laser interferometer manufacturers and sellers, respectively.

2. Theory

It is commonly known that there are 21 sources of kinematic inaccuracy accompanying spatial movement of a body in three axes [2-4]. In linear motion, this is reduced to 9 sources of kinematic errors. When measurement is done with the arms, the primary source of errors, in accordance with the Abbe principle, is the measuring arms’ length. Therefore, the most accurate part must be the guide ruler and the flatness of the base surface. The most beneficial arrangement based on this principle is when the arms are non-reconfigurable. All other moves required to measure the dimension must be done by the object. These moves are another source of errors, but they are second-order errors. These are mostly cosine errors. The nature of the measuring contact is a force which acts not only on the object but also on the end of the measuring arm. This force must be minimized to avoid arm deformation [5]. Deformation propensity increases with the increase of the arm length. On the other hand, the arm length determines the range in which the object can be measured. Ideally, a proximity sensor should be used. However, there is a risk that such sensors will not determine a clear distance from the surface due to roughness and type of the material. A compromise solution is to use a special contact sensor with a small and precisely defined contact force. For the methodology proposed, a high sensitivity sensor should be used. Linearity requirements are smaller, because repeated measurements must always be made to the same load of the sensor. However, this last requirement gives rise to special demands on positioning accuracy of the interferometer component carrier [6].

Naturally, thermomechanical sources of errors may also occur. In this respect, the proposed measurement methodology poses an advantage, because the measurement starts with the system reset. If the whole system is therinally stabilized, this error source is also minimized by resetting the system before the measurement, and the error increases only with the increased time of measurement duration. This even has an advantage over conventional CMM systems, where the temperature compensation needs to be ensured by means of a complex system design.

3. Measurement procedure

The first step in the measurement is resetting the measuring system. Measuring contact sensor heads at the end of the measuring arms are aligned co-linearly (Figure 1). Resetting is done when both sensors touch by gently bringing the interferometer to the reflector. The laser system is reset and the values of the contact sensors, the accuracy of which corresponds to the accuracy required, are recorded.

The second step is the separation move of the arms, which creates space for the object to be measured in. The object is inserted into this space so that the desired dimension is measured exactly in the axis of the contact sensor.

The third step is moving the reflector arm to touch the object. At this step, the value of the contact sensor recorded at reset has to be obtained.

The fourth step is the same as the third step but the contact is achieved with the interferometer arm. When the correct contact is achieved, the laser display shows the dimension measured.

When determining a different size, the system does not need to be reset. All that needs to be done is moving the arms away from the object, and after setting a new position or inserting a new object, the procedure can be repeated from step three. If there is considerable thermal expansion between the measurements, it is advisable the system be reset before starting a new measurement.

The accuracy and reliability of the measurement can be increased by eliminating random error resulting from dynamic motion of the arms. Position verification in this case can be performed by a set of repeated micro-arm movements in the alternating direction around the contact point. The most frequent value obtained by the measurements is considered to be the correct value.
4. Experiments to verify contact impact during measuring

The most important part of drafting the measurement methodology is to verify the contact of the measuring arm with the object measured. This task gives rise to a lot of possible influences, which will definitely affect the design of the measuring equipment’s correct rendering. Problems arise in precision positioning, in setting the arm stiffness and the in selecting the correct contact sensor.

4.1. Arrangement of the contact-measuring experiment

The highly accurate digital GT2-P12KL sensor from Keyence was used to verify the contact force. The sensor accuracy is 1 μm and its resolution is 0.1 μm. The XL80 laser from Renishaw was used as a laser system. The laser system precision is ± 0.5 μm/m. A 500 mm, DIN 874/00 knife straight edge was used to guide the carriers. The system is set on a granite measuring slab 5000x400x100 mm. Figure 2 describes the experiment arrangement. The principal arrangement is shown in figure 3.
The length of the arm from the laser beam axis is 180 mm. The arm carriers have a three-point contact with the measuring board and a two-point contact with the knife ruler. Two-sided arm was used to balance the carrier stability. To eliminate the backlash in the motion along the ruler, weight on a rope transmission was applied.

4.2. Contact counterbalance spring and measuring the contact stiffness
To minimize the contact force, the sensor was counterbalanced by a preloaded spring. The magnitude of contact force dropped from about 0.14 N to 0.007 N. The principle of negative spring preload allows for a significant reduction in the contact force (Figure 4).

4.3. Repeated contact measurements
Repeated contact measurements enable to determine the accuracy of the measurement under the given conditions. Figure 5 shows 32 repeated measurements. The biggest problem was encountered in positioning the carrier arm. Manual position tuning brings considerable scatter of measured positions to the system. For practical purposes, it is worthwhile to use a motor drive in this respect.

Based on the evaluation of deviations in the logs from two positions, the scattering of the sensor contact is about ± 9.5 μm (the confidence interval is in the 4 sigma range). This is insufficient for precise measurement. The accuracy of the contact sensor is considerably higher. The measurement error is affected mostly by dynamic phenomena occurring during changes in position. The magnitude of the contact force acting on the carrier arm is assumed to have less influence. Motorically driven micromotions can greatly improve accuracy. This has been proven by preliminary experiments measuring the contact of the carrier with the object of measurement. The contact was repeated by the contact force relief by means of motoric drive. The contact force was generated by the weight through rope transmission. The results were significantly better than those achieved by manual positioning. Figure 6 shows the results of repeated measurement of the contact of the carrier with the measured object. Only
values that were repeated several times were selected to determine the actual dimension. In this case, precision is determined in the order of a tenth of a micrometer.

Figure 5. Logs of repeated measurements by the sensor contact.

Figure 6. Log of repeated measurements of the carrier contact by means of motoric drive.

5. Design of the future device
Device design is based on experimental experience. The first proposal’s idea was that the measuring arms would be adjusted during measurement. Such intervention, however, introduces a first-order error into the measurement. Therefore, the best length measurement philosophy is that the arms are not reconfigured and that all the adjustments needed to measure the size are carried out by the measured object. In this case, moving the object causes a second order error. In this respect, the measuring configuration consists of two separate parts. The first part consists of a measuring ruler with the laser interferometer carrier and the arms fitted with the contact sensors. The second part is a measuring jig handling the measured object. The measuring jig ensures that the correct position is achieved relative to the measuring arms, that the object is removed from the measuring zone after a change in the measured dimension or before the system is reset. If a rotary table is located on the measuring jig, this is an advantage.

Measuring surface plate is not required for measurement purposes. Precise guideway of the carriers can be ensured by two parallel knife edge. This part requires the most accurate execution. Any deviation from linearity causes angular rotation of the measuring arm, which results in the greatest contribution to the measurement error. For this reason, it is suitable for the arms to be as short as possible. On the other hand, by shortening the arms, the measure range is limited. The compromise solution is to use
exchange arms of different lengths. The guideways should be in horizontal position, which is properly achieved by a three-point arrangement.

To ensure accuracy, it is also necessary to deal with the axial alignment of contact sensors. The sensors should terminate in a sphere shape. Co-ordination could be set up with a measuring instrument. A better solution is to use the laser interferometer itself.

The contact sensors usually have a high contact force. Proximity sensors are highly sensitive to the object changing the environment and the position. Therefore, it is suitable to produce a combined sensor. The sensor measuring head operates on the proximity principle. For example, the capacitive sensor achieves very high accuracy [7]. The end of the head is the contact part, which has a small stroke, very low stiffness to the axis of measurement.

Figure 7. Design of the future measurement configuration.

6. Conclusion
The laser interferometer measuring equipment does not replace conventional measuring systems. The system can only be used where a Michelson laser interferometer is already available. On the other hand, the measuring equipment expands the possibilities of its use. The measurement methodology itself is progressively designed to eliminate the effect of the thermal expansion of the measuring system. This achieves a very high accuracy of measurement. The method provides the ability to measure the length dimensions of static objects at a given level of accuracy. But it is a less accurate method than the direct measurement of moving objects by laser interferometer.

Acknowledgments
This contribution has been supported by research grants: APVV-15-0149, APVV-15-0164, APVV-18-0413 and APVV-15-0295, VEGA 1/0224/18, VEGA 1/0098/18, VEGA 1/0556/18 and VEGA 1/0437/17, KEGA 006STU-4/18, KEGA 025TUKE-4/2019 and KEGA039STU-4/2017.

References
[1] Hillard R L and Shepherd G G 1966 Wide-angle Michelson interferometer for measuring Doppler line widths *JOSA* 56(3) pp 362-69
[2] Schwenke H et al. 2008 Geometric error measurement and compensation of machines—an update *CIRP Annals* 57(2) 660-675
[3] Abbe E 1890 Messapparate fur Physiker *Zeitschrift für Instrumentenkunde* 10 pp 446-447
[4] Dassanayake K M; Tsutsumi M and Saito A 2006 A strategy for identifying static deviations in universal spindle head type multi-axis machining centers *Int. J. Mach. Tool. Manu.* 46(10) pp 1097-106
[5] Cauchick-Miguel P A and King T G 1998 Factors which influence CMM touch trigger probe performance Int. J. Mach. Tool. Manu. 38(4) pp 363-374.

[6] Stamenkovic M 2007 Method and device for the three-dimensional measurement of objects U.S. Patent No 7 310 889

[7] Dean T J, Bell J P and Baty A J B 1987 Soil moisture measurement by an improved capacitance technique, Part I. Sensor design and performance J. Hydrol. 93(1-2) pp 67-78