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INTERFEROMETRIC SET-UP FOR MEASURING THERMAL DEFORMATIONS OF PRECISION CONSTRUCTION ELEMENTS

Marek Dobosz, Mariusz Kożuchowski, Marek Ściuba, Olga Iwasińska-Kowalska, Adam Woźniak

Warsaw University of Technology, Faculty of Mechatronics, Św. A. Boboli 8, 02-525 Warsaw, Poland (dobosz@mchtr.pw.edu.pl, M.Kozuchowski@mchtr.pw.edu.pl, M.Sciuba@mchtr.pw.edu.pl, iwa@mchtr.pw.edu.pl, ✉ *wozniaka@mchtr.pw.edu.pl,* +48 22 234 7665*)*

Abstract

Many precision devices, especially measuring devices, must maintain their technical parameters in variable ambient conditions, particularly at varying temperatures. Examples of such devices may be super precise balances that must keep stability and accuracy of the readings in varying ambient temperatures. Due to that fact, there is a problem of measuring the impact of temperature changes, mainly on geometrical dimensions of fundamental constructional elements of these devices. In the paper a new system for measuring micro-displacements of chosen points of a constructional element of balance with a resolution of single nanometres and accuracy at a level of fractions of micrometres has been proposed.

Keywords: interferometric measurements, thermal deformations, precise balance.

1. Introduction

Many precision devices, especially measuring devices, must maintain their technical parameters in variable ambient conditions, particularly at varying temperatures. An example of such a device may be a super precise balance produced by Radwag [1]. This device must keep stability and accuracy of its readings in varying ambient temperatures. Due to that fact, there is a problem of measuring the impact of temperature changes, mainly on geometrical dimensions of the device's fundamental constructional elements. An assumption was made that precise balances should operate in air-conditioned laboratory conditions, where the ambient temperature is kept equal to approximately 20°C and allowed changes in temperature can be very slow (*e.g.* 1°C/h). Due to the size of construction parts that ranges from single to several centimetres, we had to be prepared for dimensional changes ranging from fractions to single micrometres. This meant the necessity to develop a system for measuring micro-displacements of chosen points of a balance constructional element with a resolution of single nanometres and accuracy at a level of fractions of micrometres. In order to analyse the impact of temperature changes on the geometrical changes of elements, a need emerged for setting the temperature changes with high accuracy and stability (at a level of 0.01°C per 8 hours), while keeping minimal (below 0.01°C) gradients of temperature in the environment of a tested element. It could seem that the problem of setting the temperature changes of a tested element can be solved by using climatic chambers available on the market.

Typical temperature changes in the available climatic chambers which could possibly be used range from zero to tens of degrees. While the range of temperature changes exceeds the required one, also accurate setting temperature and distributing it appropriately inside the chamber becomes a problem. It has been proved that typical accuracies of the set temperatures are about 0.1°C with gradients inside the chamber reaching 0.2°C [2]. This meant the necessity

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of developing a specialized research set-up including a chamber and a system for non-invasive measurement of micro-displacements.

In this paper we demonstrated a set-up with a temperature stability level in the chamber reaching the value of 0.01°C per 8 hours. This value is at least about one order of magnitude better than that offered by commercially available climatic chambers.

The described optical set-up in the chamber is able to measure components of various scale. Most of the known solutions are designed to measure a thermal expansion coefficient of the prepared block or tube samples [3−5] and gauge blocks [6]

2. Construction of appliance

The analysis of the problem has led to the following general concept of the measuring set-up. It is composed of two basic units: a thermal chamber for setting controlled changes in temperature of a tested element and a laser interferometric system for measuring micro-displacements of a chosen test element. Inside the chamber, there is a unit of the measuring interferometer. The tested element is placed on a base made of a material with almost zero thermal expansion coefficient.

2.1. Thermal chamber for setting changes and stabilizing ambient temperature

The purpose of the chamber is to stabilize air temperature at a level of 0.01°C per 8 hours in the points ranging from 15 to 35°C, chosen by the operator. In the stabilized area, long-term interferometric measurements are to be performed, thus the level of temperature stability is the main parameter of the set-up. Therefore, when developing the concept and construction of the chamber, the greatest emphasis has been put on the elements affecting the level of obtained temperature stability, then − on the dynamics of changes between thermal points set by the operator.

Chamber assembly and its power supply

Precise setting of temperature in a volume not exceeding 0.5 m^3 requires extremely precise control of the heat flow. Thus, semiconductor Peltier modules were applied as a thermal pump, which − due to a close relationship between the current and supply voltage and the efficiency of heating and cooling − enables precise controlling the heat conveyor. In the chamber there are to be performed long-term measurements of the dimensional stability of metal elements with the use of interferometric technique. As the target level of uncertainty of these measurements is expected to be several to several dozen nanometres, it was crucial to minimize temperature gradients in the stabilized space, as well as to reduce mechanical vibrations caused by the system of temperature stabilization. These vibrations would affect the readings of the interferometric system. In order to minimize mechanical vibrations, two technical solutions were applied. First, the chamber was put on a special table, the top of which floats on airbags and its construction is optimized with the use of vibro-insulation.

Secondly, the system has been divided into two parts: the chamber and a separate system of setting changes and stabilization of temperature. The temperature in the chamber is set with the use of a water jacket surrounding all walls of the chamber. The water jacket is made of flexible plastic tubes transporting liquid of a predetermined temperature. The applied water jacket surrounding the entire chamber separates the stabilized area from external conditions. Additionally, it ensures a proportional distribution of heating and cooling of the entire volume of the chamber, what minimizes thermal gradients and eliminates the need for forced (*e.g.* by ventilators) air mixing. The water jacket is supplied with water from a tank located on a rack not mechanically connected with the chamber. In the tank, the temperature of water is stabilized and then provided to the chamber by flexible hoses. Thanks to the separating the chamber from the system controlling temperature, vibrations of the necessary ventilators responsible for heat removal from cooling/heating elements (peltiers) of the electronic system are not transferred into the thermal chamber.

A schematic diagram of the appliance is presented in Fig. 1. The climatic chamber (1) is placed on an optical table (2), characterized by a high mechanical stability due to using the honeycomb structure in its interior. The whole is supported by vibro-insulation legs (3), containing pneumatic systems levelling the table. The water jacket of the chamber is supplied with water from a tank (4) with a capacity of about 25 litres. It is covered by a 5 cm layer of styrodur (5) separating the stabilized liquid from influence of the ambient temperature. The liquid is transported to the chamber through flexible hoses, its circulation is forced by a set of pumps (6). Change of temperature in the tank is controlled by Peltier modules (7), which are put between two water blocks acting as heat-exchangers between the liquid and the surface of the modules. Heat flows between the hydraulic circuit of the chamber and the system supplying or receiving heat from Peltier modules. This system consists of pumps (8) and an air cooling system (9), the efficiency of which was improved by adding ventilators forcing the air flow. At the highest point of the system surge tanks are located (10), the task of which is to maintain an adequate level of liquid and to compensate its thermal expansion. An electronic module (11) is responsible for controlling the Peltier module.

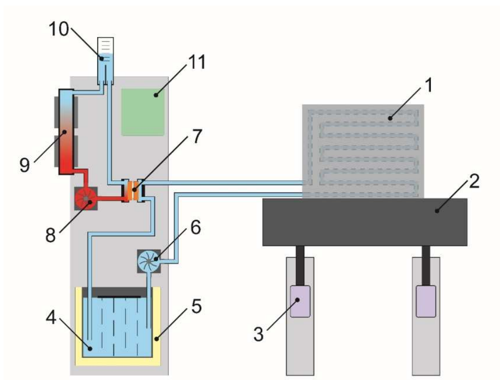


Fig. 1. A schematic diagram of the set-up for temperature stabilization in the chamber with an interferometer.

Chamber construction

In order to obtain a stable temperature in the chamber without the necessity of additional air mixing, we decided to create a water jacket, which surrounds the stabilized space. There were used specialised synthetic hoses, with their construction optimized by reducing internal wall roughness and increasing a bending radius. It influenced the resistance of liquid flow and enabled to avoid folding a hose when putting it in the walls of the chamber. Since the total length of the hydraulic circuit in the chamber is 45 meters, reducing the flow resistance was crucial for obtaining an appropriate capacity of the system when using pumps which – while ensuring negligible pressure (and vibration) fluctuations – were characterized by an insignificant pressure.

The structure of the wall and chamber base is presented in Fig. 2. Hoses (2) were squeezed between the inner wall of the chamber (1) and the intermediate wall (4). This was made in order to increase the contact surface of the hoses with the chamber walls, making the flow of heat more efficient. Moreover, the chamber had to be made of non-magnetic elements. Sheet metal was good heat exchanger with the interior of the chamber and at the same time distributed heat evenly. The hose system was separated from the surroundings with a layer of foamed polystyrene (3) to reduce a power loss in the system stabilizing the liquid temperature. The whole was surrounded by painted stainless metal sheet (5).

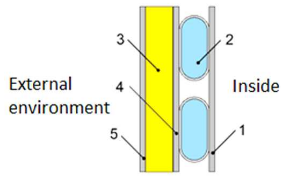


Fig. 2. The structure of the thermal chamber's wall.

The base of the chamber was integrated with the optical table equipped with threaded holes. They enabled pulling the hoses to the top of the table, which thus was thermally stabilized, just like the interior of the chamber. This was a barrier to the influence of ambient temperature on the chamber's space. Additionally, the thermal stabilization of the top of the table improved the mechanical stability between the measured elements in the chamber and the located outside the chamber elements of measuring interferometer, which was mechanically linked to the top of the table. In one of the side walls of the chamber, two electric passes were made with cable connectors for insulation and an optical hole enabling to introduce a laser beam of the interferometer into the chamber. The assembled chamber is presented in Fig. 3.

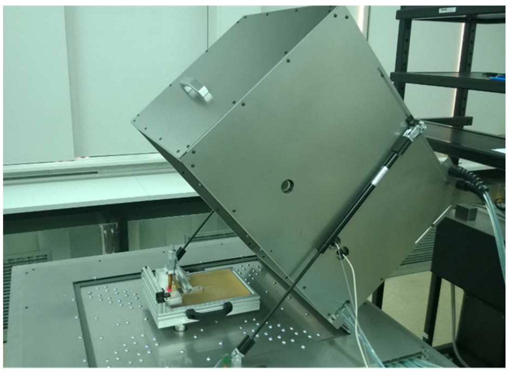


Fig. 3. A view of the chamber together with the table and elements of interferometer.

2.2. Measuring base

In order to enable thermal measurements of the changes of geometrical dimensions of small elements, it was necessary to solve the issue of thermal expansion of the base to which a tested element was attached. The theoretical analysis of the problem proved that, in general, the only solution was the application of a measuring base made of material of a negligibly small coefficient of thermal expansion. Such materials are special optical glasses, from among which we selected ZERODUR glass manufactured by the Schott company. The coefficient of thermal expansion of this glass in the described application can be regarded as zero ($\alpha = 0.1 \cdot 10^{-6}$ K^{-1} [7]). We ordered a ZERODUR plate of the following dimensions: 140 × 260 mm^2 and a thickness of 25 mm. It is used as a measuring base, on which we place elements which geometrical changes caused by temperature changes are measured.

Inside the chamber there is a table (Fig. 4) supported by 3 legs screwed into the top of the optical table. The legs are equipped with cermet balls, that penetrate into appropriate sockets in the base of the table. The result is more repeatable attachment of the table to the chamber and the measuring system, as well as a reduced heat flow between the table legs and the table itself. The base of the table is made of an aluminium plate, with the previously mentioned glass base plate put on it.

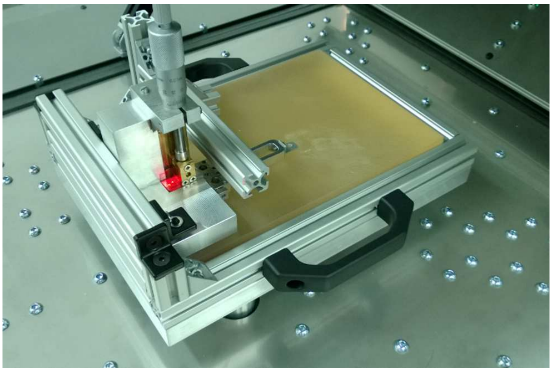


Fig. 4. A view of the chamber together with the table and elements of interferometer.

2.3. Construction of system of temperature stabilization

General concept and mechanical assemblies

Setting temperatures in the chamber is possible due to the application of Peltier modules as bi-directional heat pumps. Four Peltier modules were used with a total, maximum cooling capacity of 350 W and a heating power of 1000 W. Such a disproportion results from the efficiency of the mentioned modules. In order to receive power from the modules, they were placed between water blocks (Fig. 5). A water block consists of a copper element, its flat side adjacent to the module and the other one ribbed specifically in order to increase the contact between the metal surface and the flowing water. The stream of liquid is directed into the ribs of the copper element by a system of channels in the housing of the water block made of a temperature- resistant synthetic material .

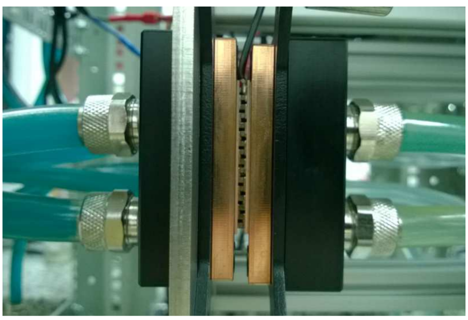


Fig. 5. A Peltier module between water blocks.

The liquid in hydraulic circuits is distilled water with addition of inhibitors, which aim is to stop or significantly slow down the reactions between the components of hydraulic circuit made of different metals. Distilled water provides a very good thermal conductivity while being neutral to the environment and the operator, as the stabilization tank is not hermetically sealed in order to compensate for the thermal expansion of the liquid.

A hydraulic circuit responsible for exchanging heat from Peltier modules with the environment is presented in Fig. 6. In the bottom part, above the tank, where the liquid for the chamber is being prepared, four pumps are located. Each Peltier module has an individual hydraulic circuit. The use of the same models of elements in each circuit provides a similar cooling capacity, flow and temperature. The pumps has been placed at the lowest point of hydraulic circuit so as to be influenced by a possibly high static pressure. These pumps provide a stable flow with no significant pressure fluctuations. The pumps send liquid directly into water blocks of the Peltier modules, which then goes to the highest points of the circuit tanks. Plexiglas expansion tanks enable to control the liquid level and to pick up gas bubbles emerging in the liquid. They also have an internal dividing wall with its inside dimension a few times larger than the diameter of hoses supplying liquid. It slows down the speed of water flow what enables to surface the bubbles and to eliminate them from the hydraulic circuit. The surge tank liquid is transported to a set of radiators. They are made of copper in order to increase the heat flow efficiency. Each radiator is equipped with four ventilators. Two of them inject air into the radiator and the other two suck it out from the other side. As a result, the efficiency of the radiators has been improved several times. It is highly important because of the Peltier modules' properties. Their maximum cooling power is inversely proportional to the generated difference of temperatures between their ceramic covers. The higher the temperature difference, the lower the efficiency of the module. This means that the more effectively the heat is received and the warm side of the module is cooled down, the lower temperature can be achieved on the cool side.

Fig. 6. A hydraulic circuit of the heat exchanger.

Electronic control - temperature regulator

As already mentioned, the air temperature regulator in the measuring chamber is based on the stabilization of temperature of the liquid flowing through the walls of the chamber. Adjusting the temperature of the liquid assures a higher stability of temperature and its more precise regulation (related to a heat capacity of the unit). The electronic system controlling temperature stability has been divided into the following blocks:

- the main controller;
- controllers of power stages;
- temperature measurement systems;

– a power supply.

The main controller is a system controlling particular modules and is responsible for:

– communication with the control master computer (setting temperature changes, sending the results of measurement to the master computer, determining the operation mode);
– communication with temperature sensors (through intermediate processors used because of the necessity of changes in the transmission protocol, as well as for reducing the distance between processor and sensor);
– implementation of an algorithm of temperature regulation;
– controlling power stages (regulation of the level of heating/cooling);
– controlling correctness of the system operation.

The power controllers are systems supplying Peltier modules which enable:

– regulation of the power supply of the module (and the related efficiency);
– switching between the heating/cooling functions.

The temperature measurement is carried out with the use of integrated semiconductor thermometers of ADT7320 type with a high measuring accuracy (0.2ºC guaranteed with no additional calibration, 0.002ºC typical accuracy and repeatability better than 0.02ºC). Thus, such systems are equipped with an SPI interface and an additional microcontroller located near the thermometers, applied to control the measurement and to send the results to the main controller via an RS485 interface. Separating the microcontroller from the temperature sensor is necessary to reduce the influence of heating of the microcontroller on the measurement.

Communication of the main controller with other modules is made on the basis of an RS485 interface (two channels). It enables a two-way transmission between multiple systems with the use of two wires. If necessary, it makes possible adding other systems without a need of rewiring.

The entire system is supplied from a 24V 1000 W chopper power supply. Each plate has local stabilizers generating voltage necessary for the operation of each module. The power control modules need 190 W each when fully controlled. Other systems take approximately 3–4 W.

The main controller is made on the basis of an ATMega64 microcontroller. Additionally, it has two UART hardware systems that are used for transmission to sub-systems. UART conversion systems – RS485 (SN75176) and USB-FT245 bridge are located in the surroundings of the microcontroller. SN75176 (U4 and U5) systems convert TTL level signals (RxD and TxD of the processor) into differential signals required for the RS485 transmission. Since it is two-way transmission, a signal of choosing the transmission direction is required. In order to ensure correctness of the transmission and protect it against a possibility of simultaneous transmission through different systems, the receiver module is still on and the microcontroller is able to view the signal on the main line. If the received signal is in accordance with the sent one, the transmission is correct.

To communicate with the master computer, an FT245 (USB converter) system has been used. This system is seen as a serial port, what simplifies the control (it is possible to use the terminal for sending and receiving data).

An LCD display is used for indicating a current condition of the processor and peripheral systems. It enables to display current settings of temperature, the results of its measurement and to signal whether the system is currently in a heating or cooling mode.

The system of power supply and control of the Peltier modules has been made in the form of four identical control modules. These modules enable independent controlling any voltage of any polarization (as regards the voltage of Peltier cells operation) of one of the four cells.

The adjustable power supply is a pulse converter lowering the supply voltage (24 V) to the voltage required by a Peltier cell (0–16 V) at the required load current equal to 10 A. The converter is controlled by PWM signals from the outlets of the processor. The PWM signals are provided to the inputs of the controller system of IR2113 transistor half-bridge, which gives a current output sufficient to drive the power transistors. A frequency of PWM is 55 kHZ. The PWM is operated on 55% and 35% cooling and heating duty cycles, respectively. These values were determined to achieve similar speeds of heating and cooling.

At the same time, this driver provides voltage higher than the power supply voltage, what is required for correct operation of the keying transistor. As the module must provide a change of polarization of the output voltage that is required to switch between the heating and cooling modes, it was inevitable to use an H-bridge for producing the switching voltage.

To reduce the influence of other elements on the temperature sensors (especially when heating), the systems were located on the plates only with elements reducing interference. In order to provide a good heat exchange with the environment, the elements were assembled on the aluminium base.

As thermometer systems are equipped with an SPI interface, it becomes necessary to use an intermediate microprocessor system between the thermometer and the main controller module. This intermediate system is based on an ATMega8 microcontroller. It provides control of 4 digital thermometers, as well as communication with the control module via an RS485 interface.

The microcontroller controls the thermometer system in such a way that temperature measurements are made at intervals of 1 second, with the maximum resolution of thermometers.

Between the measurements the systems are put to sleep, what reduces the heating of thermometers.

3. Measurement of micro-displacements

3.1. Assumptions for construction of specialized interferometer

Measurement of the geometrical changes of mechanical parts having dimensions starting from a few centimetres at a change of temperature to 10ºC requires providing a measurement resolution of displacements of a nanometre level. In practice, this means the need for applying an interference method.

Because of testing the influence of ambient temperature on an examined element, we were not able to use incremental or contactless encoders, which would require placing a detector in the thermal chamber. Due to that fact, we suggested a solution in the form of a laser interferometer, where a laser beam would be brought to the thermal chamber from the outside.

Assuming the use of a conventional interferometer with a reflector operating in one of its arms for measuring displacements of often quite flexible mechanical elements of the balances, it was necessary to adopt the following assumptions:

- minimization of weight, and thus a size of the measuring reflector together with its fastening, what leads to:
- inability to precisely adjust the position of the reflector towards the laser beam (an accuracy of linear – in the order of 0.3 mm, and angular positioning – in the order of 1º).

Taking the above into consideration, it was necessary to use a cube corner prism of possibly small weight and small dimensions as the measuring reflector. It resulted in another problem – commercially available prisms having such small dimensions are characterized by low accuracy (non-parallelism of the outgoing beam to the incoming beam is approx. 15”). This means that conventional reading systems of interferometers designed to operate with prisms of 2” accuracy are not suitable for use in this case. That is why it was necessary to apply a special receiving system of interference fringes which would give a correct reception of a signal disturbed as a result of the non-parallelism of interfering beams.

The above mentioned problems led to the need of developing from scratch a specialised laser interferometer which could operate according to the principle of counting interference fringes.

3.2. Description of construction

Laser

When constructing the interferometer, we assumed the use of a single-frequency He-Ne laser-based interferometer. The rationale is a simple construction providing significantly lower costs of construction and the possibility of greater miniaturization of the measuring system, while homodyne are similar to heterodyne systems in terms of their metrological parameters. The final argument for selecting this type of solution was adopting the concept of a receiving system insensitive to the interference angle, which, by definition, cannot operate on high frequencies of signals.

Due to a variable difference in optical paths, which may occur when measuring elements of different dimensions, it was indispensable to use a stabilized He-Ne laser. A requirement was formulated that the uncertainty of determination of light wavelength is at a level of 0.001 nm what gives a relative measurement error of displacement coming from this source at a level of $1.5 \cdot 10^{-6}$ nm. Such a value is entirely sufficient due to a small range of the measured displacements. As an example, when measuring changes in the dimensions of elements of the order of 10 µm, this component of uncertainty will generate a negligible error of $1.5 \cdot 10^{-2}$ nm.

A two-frequency Thorlabs HRS015 laser has been used. In the further described system, only one mode was used.

General configuration of interferometer

A general scheme of the interferometer with particular subassemblies, is presented in Fig. 7.

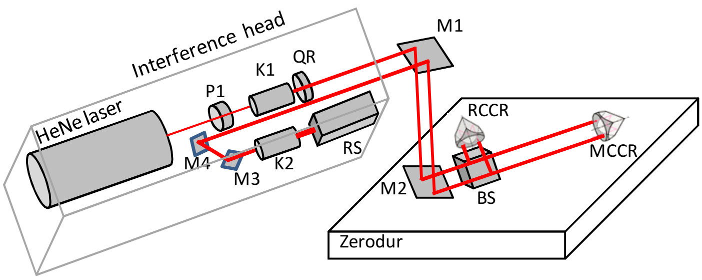


Fig. 7. A general scheme of the interferometer construction.

At the beginning, from the beam of the two-frequency He-Ne laser, one frequency of linear polarization is separated with the use of a polarizer P1. In the next stage the beam is expanded to a diameter of 2 mm adjusted to dimensions of the applied cube corner reflectors. A collimation telescope K1 is used for this purpose. Next, the beam passes through a quarter-wave plate QR, which transforms the linear polarization into the circular polarization being an effect of putting together two linear disturbances which are mutually perpendicular and phase-shifted by 1/4 of a light wavelength. The such prepared beam is emitted outside the laser head towards the interferometer assembly. This beam is directed via prisms/mirrors M1 and M2 to a polarizing cube beam-splitter BS. The mirror M1 directs the beam perpendicularly to the Zerodur base surface. The prism M2 cemented with the beam-splitting element is moved along the axis of the beam behind the mirror M1 enabling the interferometer to operate at different heights depending on the height of measured detail. A reference cube corner reflector RCCR is cemented to one side of the cube beam-splitter. It has identical dimensions as the measuring cube corner reflector MCCR. Due to that fact, changes in temperature in the chamber change the optical paths in both cube corners in the same way, without generating an error significant for the measurement. The polarizing cube beam-splitter directs a component of type P light polarization to the referential prism and then, after reflecting the beam, directs it back to the laser head. A type S polarization component is transmitted through the beam-splitting layer to the measuring cube corner reflector which is glued to the tested surface for the time of measurement. The reflector directs the beam back to the beam-splitter, which – after passing through it – returns to the laser head. Both beams are at the beginning introduced into the laser telescope K2, which expands them to a diameter of approx. 4 mm. adjusted to the receiving photo-detection system RS.

Specialized photo-detection system

There are two main types of receiving systems of interferometer: (i) photo-detective systems operating with zones of interference fringes of an infinite period [8] (classic solution) and (ii) systems operating with fringes of a finite period [9].

As already mentioned, due to insufficient angular accuracy of the cube corner reflector-prisms applied in the system of interferometer it was not possible to apply a classic photo-detection system because of a finite and unstable (dependent on the settings of the reflector) period of the fringes. This problem has been solved by applying a special photo-detection system based on a patent [10] and developed in the Institute of Metrology and Biomedical Engineering within an earlier research project and presented in detail in [11]. The receiving system is composed of the following elements:

- birefringent wedge;
- polarizer;
- cylindrical lens;
- photodetector.

The adopted receiving system is presented in Fig. 8. When passing through the birefringent wedge W the measuring and reference beams MB and RB, respectively, having mutually perpendicular linear polarization, are refracted at different angles dependent on their own polarization. This is a result of different values of the refractive index of ordinary and extraordinary rays. The wedge is made of birefringent crystal and the refraction angle depends on the wedge direction and the angle of its cut, so behind the wedge the beams run at some non-zero angles. The wedge itself must be able to rotate in order to be regulated. Next, the set P2 polarizer brings the measuring and referential beams to the common surface in order to enable their interference. The cylindrical lens CL together with properly designed regulation of the photodetector P position enable adjusting the area of interference to the surface of the photodetector.

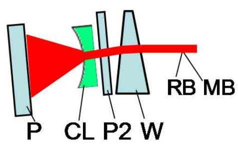


Fig. 8. A chart of the receiving system of interferometer.

Assembly of polarizing beam-splitter

The purpose of the polarizing beam-splitter assembly is precise introduction of the laser beam into the cube corner reflector placed on the tested element surface. Its construction must eliminate the influence of temperature changes on the result of measurement. A possibility of precise adjustment and fastening of the system on the measuring table is equally important as regulation of height at which the cube beam-splitter is set. These conditions are fulfilled by a mechano-optical system, a diagram of which is presented in Fig. 9. The assembly of interferometer beam-splitter is composed of three optical elements cemented together:

a rectangular prism M2 directing the beam, a polarization cube beam-splitter BS dividing the beam and a reference cube corner reflector RCCR. This assembly is mounted to a carriage, which is able to move along a slide perpendicular to the Zerodur base surface. It enables to run the measurement beam both parallel to the Zerodur base and at the desired height determined by the tested element size. The height of cube and prisms is precisely regulated by a micrometre screw

After adjusting the desired height the assembly can be stiffly fixed. Locking the assembly position by a bolt is supposed to guarantee mechanical stability of the beam splitting assembly during measurements. It was extremely important to design a stable attachment of the assembly and the tested detail together with the corner mirror to the Zerodur plate. The point of reference which has to be provided with a possibility to keep an unchanged position is the assembly of beam-splitter together with the reference reflector. Even a slight thermal change of the position of this reference assembly may significantly affect the result of measurement. Thus, in the project of assembly construction two support surfaces were made, located symmetrically to the cube, situated in the same vertical line as its centre.

The shape and dimensions of the beam splitting element provides minimal influence of thermal deformations on the result of measurements. Fastening the assembly to the base plate may be carried out by pressing the whole assembly to the Zerodur base in such a way that the points of pressure are located symmetrically on both sides of the cube beam-splitter. However, in the majority of measurements, the assembly was stuck to the base with the use of some protruding surfaces located symmetrically in relation to the referential prism.

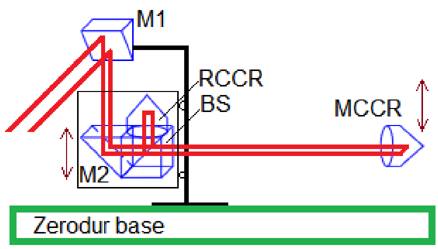


Fig. 9. A schematic diagram of the interferometer beam-splitter assembly.

Measuring reflector

The construction of measuring reflector is based on the use of a cube corner prism with dimensions enabling to work with a laser beam with a diameter of approx. 2 mm. In the project we have used an Edmund Optics corner prism with an outer diameter of 7.16 mm, what enabled to keep an optimal size of the housing with the following dimensions: $8 \times 8 \times 6.3$ mm^3. The housing of cube reflector make it possible to be mounted in various arrangements (Fig. 10).

On the external surfaces of the housing there are made outlets, one of which located on the axis of the tip of the prism can be glued at the desired point of the part, the displacements of which are to be measured. The assembly weighs about 0.8 g. An atempt was made to reduce mass of the optical element in order to decrease the influence of weight on the geometry of the measuring part. Small dimensions are required to limit the mounting area.

Attaching element to base

On each tested element two points are determined – the first, a reference point towards which geometrical changes of the detail are measured, and the second, a measuring point to which the measuring reflector of interferometer is attached. Depending on the position of base point on the part, additional intermediate elements are used. Fig. 11 a shows a fragment of the part with a hole the axis of which acts as the base point. In this case, attaching to the surface at this point was carried out with the use of a screw stuck by a conical head to the Zerodur surface and pressing the measured element by a conical nut, as shown in Fig. 11b. Depending on a form of the reference point, various specifically designed intermediate elements were used.

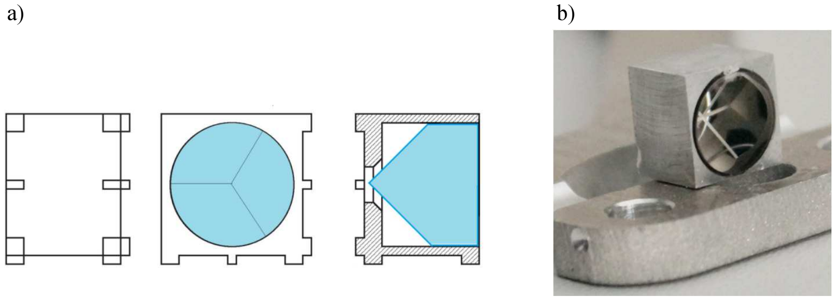


Fig. 10. A simplified design drawing of the assembly of a measuring cube corner reflector (a); a view of mounting of the measuring reflector to a tested part (b).

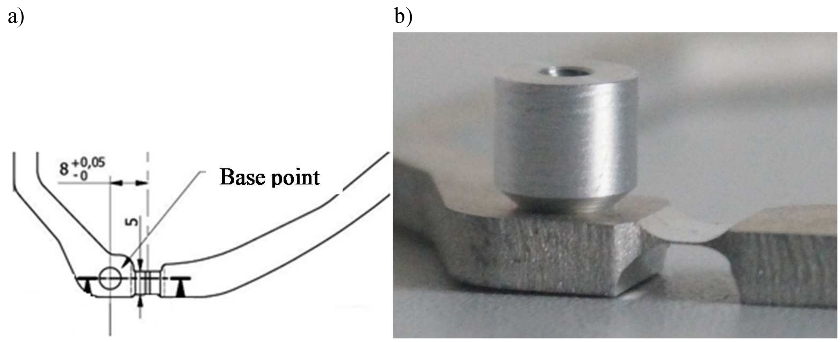
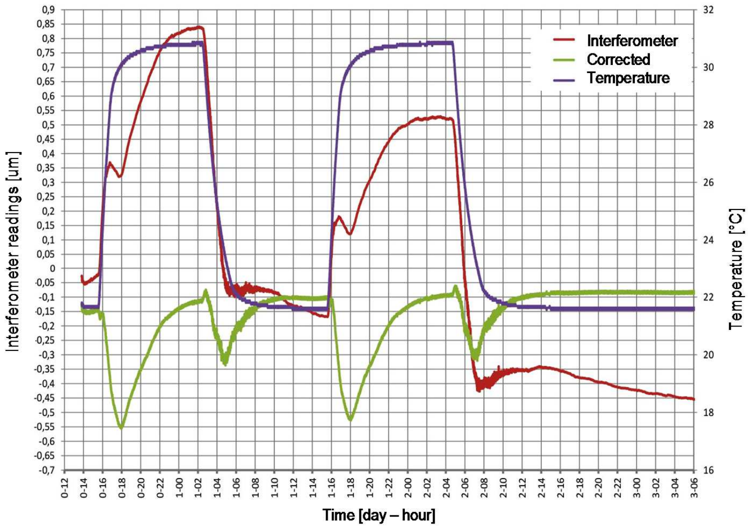


Fig. 11. Attaching the reference point to the Zerodur base surface. A fragment of construction drawing of the tested part (a); a view of a cone nut clamping the element to the base screw (b). The place of sticking the screw to the base plate is here invisible.

4. Tests of appliance and discussion

The basis for evaluation of the feasibility of performing the necessary tests using the developed appliance was verification of stability of the interferometer readings during changes of temperature in the chamber. In this case, the measuring reflector was glued with the use of its housing directly to the Zerodur base (the measured element was not used). A distance between the measuring and reference reflectors was approximately 105 mm. Next, temperature in the chamber was periodically changed and the interferometer readings were saved. Two options of data saving were used – without and with the numerical correction of light wavelength changes. The sensors of temperature, pressure and humidity installed in the chamber were used to evaluate the actual air refractive index and to calculate the actual wavelength basing on the Edlen formula [12] and its subsequent amendments [13, 14]. An amplitude of changes in temperature was 9.5ºC. The test duration was 64 hours. Sample test results are presented in Fig. 12. A purple line shows the applied temperature changes. A red line shows differences in the interferometer readings obtained without the wavelength correction. A green line shows the interferometer readings including the influence of environment on the air refractive index (and the light wavelength).

a)



b)

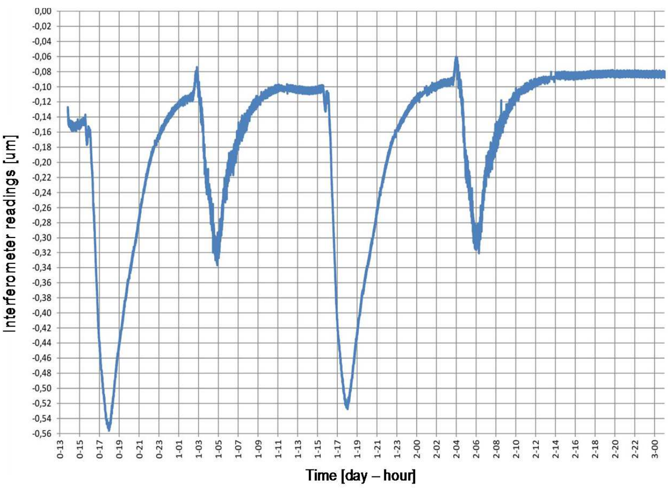


Fig. 12. Changes of the readings of the position of measuring reflector caused by changes of temperature (a); an enlarged part of the corrected readings (b).

When analysing the graph we can notice that in the first several hours of changing temperature the response of interferometer is incorrect. It results from deformation of the mechanical elements of interferometer under the influence of temperature gradients. However, after 10 hours of increasing temperature and after 8 hours of stabilization at a high level, the readings of interferometer reach a level of systematic error of about $-0.12 \div -0.11$ µm. This corresponds to the relative inaccuracy of measurement equal to approximately 10^{-6}. When cooling the chamber, stable readings are achieved slightly earlier, after about 8 hours from the beginning of cooling and after 6 hours from the beginning of stabilization in the lower temperature; the systematic error is at a level of about $-0.1 \div -0.08$ µm. This corresponds to the relative inaccuracy of measurement equal to approximately 10^{-6}. These are satisfactory values. However, obtaining this level of inaccuracy in practice requires approx. 8 hours for temperature stabilization after its change. Unfortunately, it significantly extends the duration of measurements. The noise of interference signal is a result of fluctuations of the interferometer indications caused by temperature gradients of the air in the chamber and vibration of the set-up. This random noise does not exceed 10 nm with a signal resolution of 1 nm.

If the systematic error value exceeds the required value, the only way to solve the problem is to carry out the measurement in a different way, *i.e.* with the use of a measured detail, and then without it, but with the same difference of optical paths.

The last horizontal section of the graph shows at the same time the achieved level of temperature stability in the chamber, which reaches a value of 0.01ºC per 8 hours. This value is at least about one order of magnitude better than in commercially available climatic chambers.

Summing up, the following technical parameters of the calibration system were obtained, which were confirmed by the experimental test results:

- a relative inaccuracy of displacements' measurement is equal to about of 10^{-6};
- a time interval required for stabilization of temperature (after a change of about 10ºC) in order to achieve the assumed uncertainty is approx. 8 hours;
- a level of temperature stabilization is of about 0.01ºC per 8 hours;
- a range of possible operating temperatures is equal to 15ºC–35ºC.

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