**MINISTRY OF EDUCATION**
**University POLITEHNICA of Bucharest**
**Doctoral School of**
**Industrial Engineering and Robotics**

**UPB-CSUD Decision no. 975/ 08.12.2022**

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# PhD THESIS
## *Summary*

# Contributions to structure and attributes development of laser interferometry systems

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**-2022-**

# Content

*Part II.* Contributions to defining and constructive development of laser interferometry systems structure

# Foreword

The research and development on the laser interferometry systems represent the *motivation* and *direction* of the doctoral studies, finalised by this doctoral thesis.

The doctoral activity consisted of preparation, presentation and defence of exams and scientific reports, profound study, development of defining analytical descriptors for general structure and characteristics of laser interferometry systems, proposal, design, manufacturing and validation of an innovative splitter positioning device, as part of a laser interferometry system for linear position, creating and publishing of scientific papers, as well as the elaboration of the present doctoral thesis concerning the contributions to structure and attributes development of laser interferometry systems

First and foremost, I would like to thank and praise God for making this thesis possible, and to everyone who carried me into their prayers.

I address my profound gratitude to Prof.univ.dr.ing. Marian GHEORGHE, for his scientific guidance and coordination during the entire activity of completing this doctoral program, for the support and full trust granted during this period.

I address my sincere thanks to Conf.univ.dr.ing.mat. Ovidiu BLĂJINĂ, Șef lucr.univ.dr.ing. Daniel MANOLACHE and CS1 dr.ing. Gheorghe POPAN, for their reviews and recommendations as being a part of the Advisory Committee for the doctoral scientific reports and doctoral thesis preliminary defence.

I express my appreciation and respectful thanks to Prof.univ.dr.ing. Liviu-Daniel GHICULESCU, from University POLITEHNICA of Bucharest, Prof.univ.dr.ing. Viorel PĂUNOIU – University “Dunărea de Jos” of Galați, CS1 dr.ing. Mihai MĂRGĂRITESCU - National Institute of Research and Development in Mechatronics and Measurement Technique (INCDMTM), Prof.univ.dr.ing. Nicolae IONESCU - University POLITEHNICA of Bucharest, for their comments and recommendations, as president and members of the official Doctorate Commission for scientific assessment and examination during public presentation of the PhD Thesis.

Special thanks to Ing. Nasim GANNAM and Ing. Cătălin-Ștefan NEGREA for their support to prepare and operate machining numerical centres tested through the developed laser interferometry system within my doctoral research.

I will be forever grateful to my loving brother whose words of advice never cease to amaze me with their accuracy.

This thesis is dedicated to my father and mother who raised me beautifully, always care for me and love me unconditionally. It is also dedicated to my husband, who loved, encouraged and supported me during this difficult period of time.

*Flavia-Petruta-Georgiana G. ARTIMON (STOCHIOIU)*

# Introduction

Production and measuring processes are co-dependent. Their evolution can be seen worldwide through a continuous improvement of production quality, capacity and efficiency.

The measuring processes and production systems require high precision in order to meet the product specifications. This leads to the requirement that the equipment for quality control to be able of micrometre/ nanometre scale measurements.

Since its invention in the 19th century, the interferometry method has seen a continuous development and has known a large variation of applications. Devices based on this method are some of the most precise used in measurements, in all fields of technology. For evaluating and measuring processes and production systems, it is a widely accepted and proven technology, with its nanometric precision capabilities. A restricting factor, for current laser interferometry systems, is the requirement that certain optical elements to be mounted inside the calibrated machine workspace, thus limiting the measuring range. This doctoral thesis is aimed at analysing and proposing a solution to this issue, by introducing a system structure development.

* * *

The first part of the thesis presents the state of the art on measuring processes and systems. With the aim of being aware of the various factors that may intervene into the quality results of the production and measuring systems, the metrology, quality control and standards concepts are elaborated. Further, classifications of the existing measuring devices are made and some devices are detailed. The interferometric concept, procedure and components are detailed for further studies on their capabilities.

In accordance with the data and conclusions on the state of the art research, the interferometry drew the attention, so that the main objective of the research activity was determined as: structure and attributes development of laser interferometry systems.

A development of defining analytical descriptors for general structure and characteristics of laser interferometry systems is proposed, at high level of generality, open to particularizations, in context, as well to other description levels.

According to the interferometry limitations previously studied, a new splitter positioning device for laser interferometry systems is conceptualized with respect to the functional and constructive characteristics required. Thus, several iterations of the product are considered, in order to obtain an optimal design. The final iteration has lattice structure integrated, with all characteristics allowing its usage with various interferometers. In order to manufacture the splitter positioning device, the design is optimized for direct metal laser sintering out of CoCrSP2 superalloy powder.

For the experimental tests, two similar laser interferometry systems are used, in consecutive tests, and in parallel tests, respectively, on different CNC machining centres, one in a laboratory environment, and other two in industrial conditions, in order to validate the capabilities of the considered systems and, implicitly, of the new developed splitter positioning device.

As potential perspective, a complex research should continue on interacting processes, analytical modelling and operational characteristics associated to laser interferometry systems, in order to develop their applications in active industrial environments.

# List of abbreviations

| No. | Abbrev. | *Significance* |
|---|---|---|
| 01 | ADC | Analog to Digital Converter |
| 02 | ASRO | The Romanian Association of Standardization |
| 03 | CAD | Computer Aided Design |
| 04 | CEN | European Committee for Standardization |
| 05 | CENELEC | European Committee for Electrotechnical Standardization |
| 06 | CMM | Coordinate Measuring Machines |
| 07 | CNC | Computerized Numerical Control |
| 08 | DAC | Digital to Analog Converter |
| 09 | DMLS | Direct Metal Laser Sintering |
| 10 | ECG | Electrocardiogram |
| 11 | EDM | Electrical Discharge Machining |
| 12 | ETSI | European Telecommunications Standards Institute |
| 13 | FEA | Finite Element Analysis |
| 14 | FEM | Finite Element Method |
| 15 | HRC | Rockwell Hardness |
| 16 | IEC | International Electrotechnical Commission |
| 17 | ISO | International Organization for Standardization |
| 18 | LCD | Liquid Crystal Display |
| 19 | LED | Light Emitting Diode |
| 20 | LIS | Laser Interferometric System |
| 21 | PA (2200) | Polyamide (2200) |

| | | |
|---|---|---|
| 22 | PSC | Process Software and Computer(s) |
| 23 | QC | Quality Control |
| 24 | SLS | Selective Laser Sintering |
| 25 | SPD | Splitter Positioning Device |
| 26 | TQM | Total Quality Management |
| 27 | VMC | Vertical Machine Centre |
| 28 | WCN | Wavelength Compensation Number |
| 30 | 3D | Three Dimensional |

# *Part I.*

# The actual state of the art on measuring processes and systems

# *Chapter* 1. Measuring processes and production systems

## 1.1. Metrology, quality control and standards

Generally, production and measuring processes for each individual product must be punctiliously prepared in order to achieve the required technical and economical product criteria.

When it comes to a production process, a general cause-and-effect diagram of this concept was determined (Fig. 1.1) [I01].

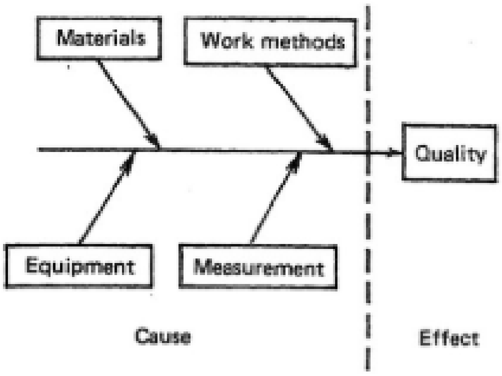



Fig. 1.1. Cause-and-effect diagram [I01]

The process that ensures that the production and measuring systems are working in the stipulated parameters is quality control.
Quality control cannot be accomplished without measurements. This concept also comprises establishing and forestalling the cause for which a product could be identified as non-compliant. Inspection and calibration are parts of quality control that encompass the scope of keeping the process up to the specific quality characteristics determined initially, through measurements [W01].

Inspection is an important aspect of quality control. Moreover, quality assurance includes all aspects of quality control and inspection, as it contains quality planning, quality inspection and quality supervision. Shortly, quality assurance is the sum of measures taken to ensure quality [M01].

Depending on their purpose, there are different types of standards oriented towards referencing, calibration, inspection or working. A brief hierarchical classification of standards is depicted in Fig. 1.3.

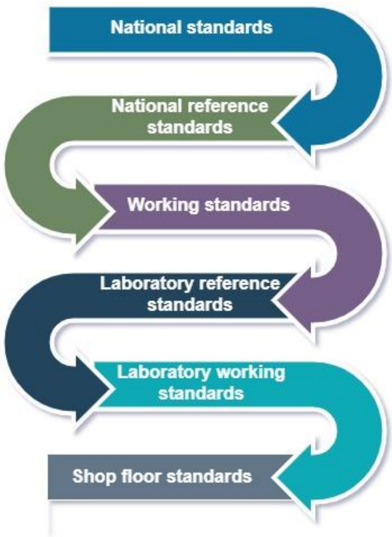



Fig. 1.3. Hierarchical classification of standards [R02]

### 1.1.1. Measuring process and characteristics

Choosing the measuring principle depends on many factors, out of which the most important could be considered the measurand characteristics, required precision, resolution, stability, environment, time, costs etc. Taking this into consideration, throughout time, numerous types of measurement procedures have been explored.

Choosing the perfect measuring device cannot be possible due to the fact that there are no ideal instruments for this type of activity and usually, the device that might offer the best response is noticeably expensive [R01]. This is one of the reasons why choosing the measuring device needs to take into account the scope of the measurement. Whether it is for study on a site, in a laboratory or in a factory, even though the measurand might be the same, the proper device might differ.

### 1.1.2. Measurement errors

A measurement error can be summarized as the difference between the measured quantity and the absolute value of that quantity. As the absolute value cannot be truly known, the real measurement error is the sum of the device measurement errors, methodological errors, human errors and statistics [G02].

While the classification can be procedure-based, errors can also be distinguished based on the factors that cause their characteristics: systematic and random. Systematic errors comprise the device, environmental and observational errors, and influence the accuracy of the measurement, while random errors are frequently caused by an unexpected variation of the work environment and influence the precision of the measurement results. [R01]

Mathematically, the relationship between accuracy/inaccuracy, repeatability and systematic errors can be described as [G02]:

$$Accuracy = \sqrt{(repeatability)^2 + (inaccuracy)^2 + (systematic\ errors)^2} \tag{1.1}$$

A Gaussian description of random and systematic errors is depicted in Fig. 1.7. As it may be noticed, the actual result of a measurement may be written as [G03]:

$$Result = true\ value + systematic\ error + random\ error \tag{1.2}$$

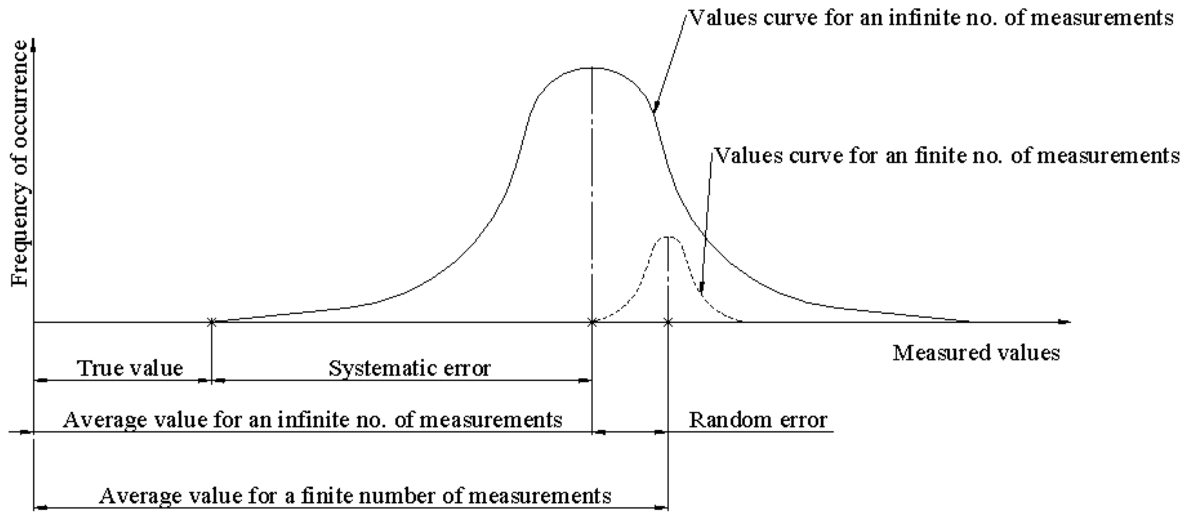



Fig. 1.7. Random and systematic errors description [adapted from I06]

Unlike random errors, systematic errors are easy to notice and evaluate, cannot be eliminated by increasing the number of measurements but can be reduced by device calibration. Moreover, random errors are characterized by variance, standard deviation and mean, and can be both positive and negative [R02].

## 1.2. Production and measuring process inspection

The sum of tests and verifications performed on measuring and production equipment represents an inspection procedure [B01]. When performing an inspection on an equipment, guidelines may be provided by the manufacturer but, usually, this procedure is detailed by approved guidelines [P01]. Companies tend to develop specific technical norms for production and measuring process control in order to meet the client's needs, the equipment capacities, the staff qualifications and product specifications.

Choosing the appropriate method for inspection depends on the desired accuracy. The two are linked through the economic aspect as, an increase in accuracy usually is accompanied in an increase in costs, which can have an exponential evolution

In order to perform a production inspection, the instrument chosen to be used has to be calibrated with a device having ten times the accuracy [R02, C03].

## 1.3. Calibration of production and measuring systems

The calibration process combines a suite of operations in special environmental conditions in order to establish the relationship between a measuring system and the measurand and to eliminate the systematic errors [B02].

This procedure is applied mostly to devices, instruments and equipment of production process and metrology. Calibration is performed under specific conditions determined by standards and it refers to direct comparison of output values and the previously known dimensions or performance of the measurand.

An authorized person may perform this process and it leads to a certificate issue. If the output values exceed the tolerance values, a recalibration procedure should be operated.

One of the most important attributes of the measuring instruments is traceability. To achieve traceability, the calibration of the measuring devices and equipment by following international standards is crucial [F01].

To facilitate this traceability, international standards, considered primary, are adapted into national standards (by ASRO, for example), widely known as secondary, and to working standards (Fig. 1.11).

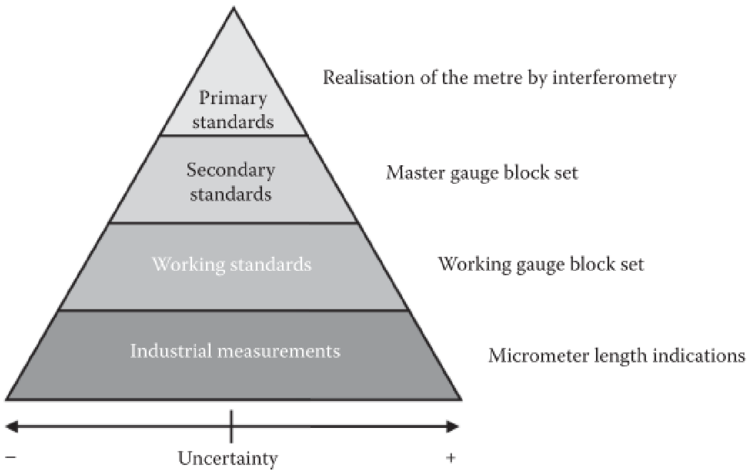



Fig. 1.11. The traceability pyramid for micrometre measurements [L01]

## 1.5. Influence of the temperature as an environmental factor

Temperature instabilities may produce extreme differences when micrometric accuracy is needed, therefore certain solutions [R04] were developed to overcome these problems. Generally, approaches focus on the sources of temperature fluctuation.

In the case of a machine-tool there are five origins of this problem: room environment, coolants, people, machine-tool and cutting process [B03]. Each source transfers heat through one of the three possible ways: conduction, convection or radiation. This heat transfer might be uniform, such as in the case of room environment or coolants sources, or non-uniform from other causes.

Temperature variations may affect dimensions of the operating device (master and machine frame) and the part/ measurand. This disturbance may produce either contractions or expansions to the material that is formulated as a multiplication of the initial length, the expansion coefficient and the temperature [V02].

The expansion coefficient indicates the deformation type by use of a positive or negative sign before the value number. Contraction is depicted in a negative form, while the expansion is positive.
In order to illustrate the temperature influence on the linear coefficient, several results from the literature [T01] are gathered in Fig. 1.14. It is noticeable that most of the listed metals behave in a similar fashion, with an increase in the expansion coefficient, with the exception of Invar, also known as FeNi36, which has a particular evolution with respect to temperature.

This iron alloy has a very low thermal expansion, at temperatures up to over 100° C. This is due to the magnetic and electronic contributions, which dominate the behaviour at low temperatures. Therefore, this material is frequently used in the construction of measuring equipment and others that require dimensional stability.

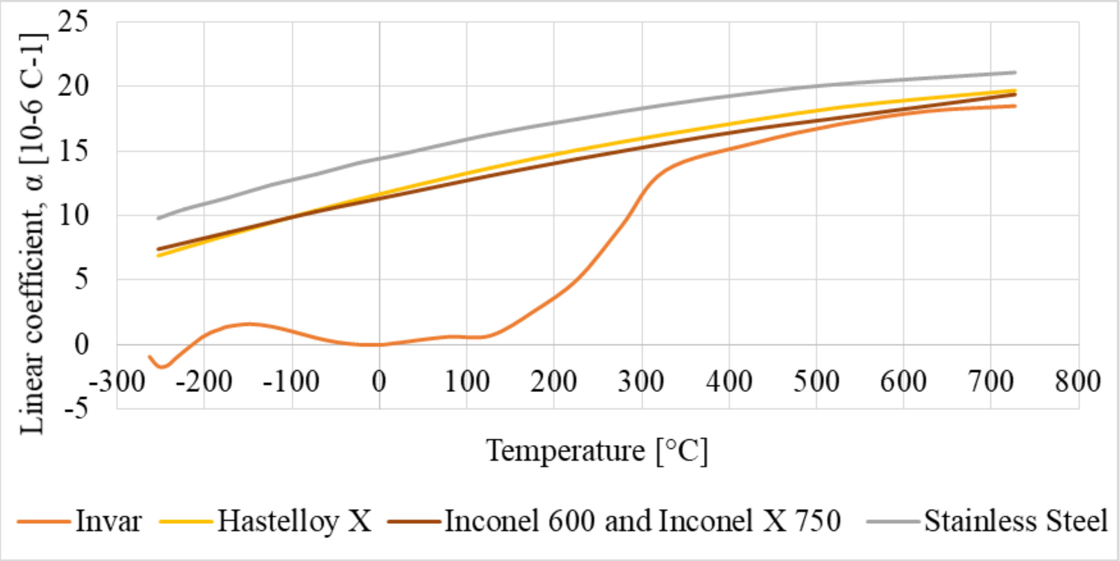



Fig. 1.14. Thermal linear coefficient for various metallic alloys

Production and measuring equipment manufacturers are continuously improving their products and the decrease of temperature influence is one of the focused improvements.

In order to avoid thermal drift during a measuring procedure, standards such as [I10] recommend soaking both the measurand and the measuring instrument in a 20° C stable environment, hence the construction of each device contains different types of materials, therefore different expansions or contractions may affect the process.

# *Chapter* 2. Measuring equipment and devices

## 2.1. Introduction

A measuring instrument is a set of technical means having the scope of establishing a quantity or a variable, considering national and/or international standards. Generally, this type of instruments is equipped with sensors and/or transducers, signal conditioning division and a signal processing stage, as presented in Fig. 2.1 [W03].

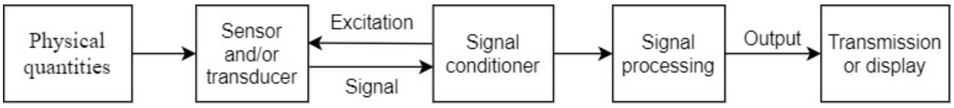



Fig. 2.1. General structure of a measuring instrument [W03]

Every device compels periodic calibration to maintain quality. When referring to the production machines calibration or even measuring equipment calibration, the most precise devices, such as interferometers, autocollimators, electronic levels, reference encoders, etc. might be required.

## 2.3. Interferometry and interferometers

Throughout time, a multitude of measurement techniques and instruments were developed, and their accuracy has improved constantly.

At this moment, one of the most accurate measurement devices is the interferometer [B06]. Albert Michelson was the first to implement interferometry in measurement in the late 19$^{th}$ Century and the working principle of all the interferometers developed until today was slightly changed.
This measurement technique is versatile, commonly being used in high quality measurements.

Interferometry has its roots into the wave theory of light which, more than 300 years ago, explained that the light behaves as waves, similar to sound [R05]. Starting from the indispensable theories of light and wave, the fundamentals of the interferometry method are derived. Light waves are composed of perpendicular electric and magnetic waveforms (Fig. 2.8).

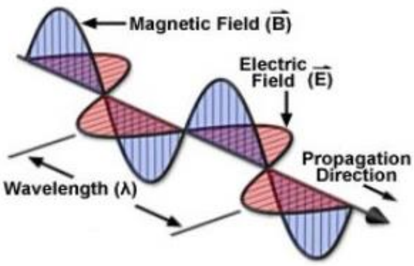



Fig. 2.8. Electromagnetic wave [B07]

Each (harmonic) wave may be described by five parameters: irradiance, phase angle, propagation direction, wavelength and direction of polarization [D02].

Those parameters change when the beam meets the measuring object. Interferometry captures those changes and studies them to acquire information about the measurand.

(a) Irradiance
Irradiance, also known as flux density of a wave, is the total energy that flows per second across a unit area perpendicular to the propagation direction. In interferometry, irradiance is also entitled as the beam intensity, being considered the beam's capacity to concentrate the energy into a specific area within a certain time. This parameter is very important especially in domains where it is used for cutting, welding or heat treatments (surgeries, metal products manufactories, etc.). Irradiance is measured in W/m$^2$ and it is proportional to the square of the wave's amplitude [R06, P03].

(b) Phase angle
The phase angle is the angular displacement of a sinusoidal wave from a given reference. It can only be measured by means of the superimposition phenomenon. Therefore, if two waves are traveling in the same direction with the same amplitude, frequency, and velocity, but one has a phase angle difference of $\phi$, their equations [S04] are:

$$Y_1 = A\sin(kx - wt - \phi) \tag{2.1}$$

$$Y_2 = A\sin(kx - wt) \tag{2.2}$$

where: A is amplitude; $k = 2\pi/\lambda$; ω - the angular frequency ($\omega = 2\pi\vartheta$); x - the direction; t - time.
If those two waves are superimposed, their waveform is given by:

$$Y = 2A\cos\left(\frac{\phi}{2}\right)\sin\left(kx - wt - \frac{\phi}{2}\right) \tag{2.3}$$

As mentioned earlier, irradiance is proportional to the square of the wave's amplitude, therefore:

$$I = 4I_0\cos\left(\frac{\phi}{2}\right) \tag{2.4}$$

where, $I_0$ is the irradiance of one of the two waves.

When two identical waves superpose in phase, the field strength doubles while when the two waves oscillate in opposite phase (superimpose), they equal out each other (Fig. 2.9) due to the fact that their field strength is calculated by summing the vectors of each field strength. In consequence, in the first case, the irradiance multiplies four times, while in the second case is null.

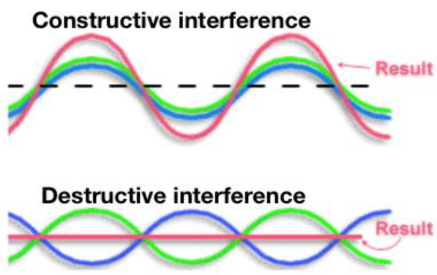


Fig. 2.9. Wave interference [I11]

(c) Propagation direction
An obvious definition is that the direction of the propagation is the travelling axis of the wave.

However, when two waves differ from each other only by their directions of propagation they superimpose creating an interference pattern that allows various measurements. The time interval between two peaks of the fringes, D, may be determined knowing the angle, θ, between the two waves, and their wavelength, λ, as:

$$D = \frac{\lambda}{2\sin\theta} \tag{2.5}$$

(d) Wavelength
Wavelength is the distance between a start point and an end point of a complete oscillation cycle. Since the sine waves are symmetric, the wavelength might also be defined as the distance between two similar points in the wave (Fig. 2.8). Previously, it has been established the importance of accuracy and repeatability, especially in precise measurements. Wavelength needs a frequency stabilization in order to provide those two characteristics, therefore all the interferometric laser sources have a stabilization mechanism [S05]. The output of an interferometric measurement are fringes. When a displacement occurs in the system, the fringes are disturbed. Each fringe represents a division of a wavelength. In order to measure those displacements, wavelength measurements, based on the superposition principle, can be approached. Being considered two waves, $E_1$ and $E_2$, with different frequencies that are superimposed. The two wavelengths, λ and λ + Δλ, lead to a resulted wave that has an irradiance modulated in time. The time interval between two peaks of the irradiance are entitled beat periods, $T_b$, and:

$$T_b = \frac{\lambda^2}{\frac{\omega}{k}\ \Delta\lambda} \qquad (2.6)$$

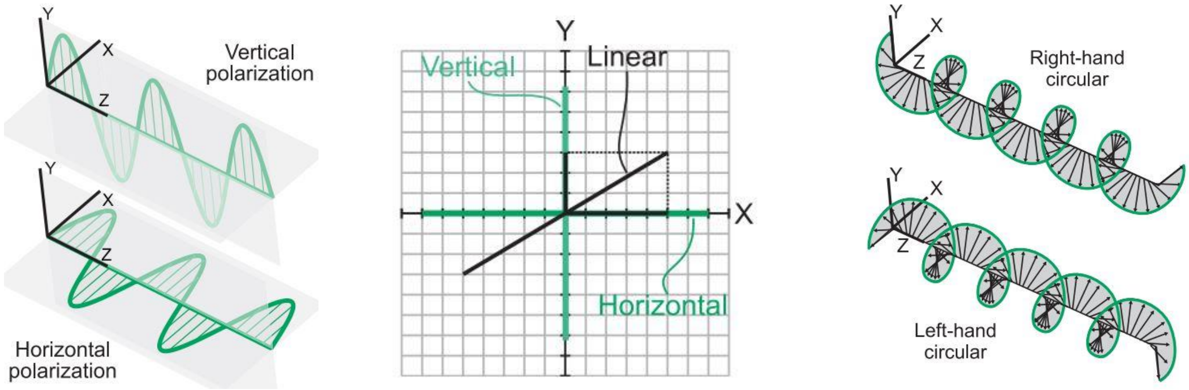
where: ω is the angular frequency, and k - the wave number.

This equation helps to identify the wavelength shift, considering an established absolute wavelength. If the measurement period is smaller than a beat period, then the beat period cannot be determined.

(e) Direction of polarization

The polarization direction is given by the transverse direction of the electric field. Generally, since the direction of propagation is considered to be along the Z axis, the light polarization is taking place in the X-Y domain (Fig. 2.14, a).

In the basic stages of interferometry, the polarization direction is linear (Fig. 2.14. b) but, usually, it acquires a more complex, elliptic or circular form. These complex forms have a 90° phase lag and their polarization direction divides them in two categories: right-hand/counter-clockwise polarized or left-hand/clockwise polarized (Fig. 2.14. c).




a) X-Y polarization direction b) Linear polarization state c) Complex polarization state

Fig. 2.14. Beam polarization direction [E02]

Light can be defined as an electromagnetic wave traveling through space. If a linearly polarized wave, is propagating along a z direction, its equation may be represented as follows:

$$E = \alpha \cos\left[2\pi\left(\vartheta t - z/\lambda\right)\right] \qquad (2.7)$$

where: α is the amplitude of the light wave; $\vartheta$ - the frequency; λ - the wavelength.

2.3.3. Common types of interferometers

Interferometry has been of particular interest endorsing various applications such as: identifying a new method of defining the meter [R07], plasma diagnostics [V03], precision industrial measurement of lengths and movement [J01, S06, S07], linear deviations and strain measurements [A04, T03, X01], gravitational antennas [K05], vibration analysis [Z01, C09], illegal mining and landslides monitoring [M05, S08], blood speed measurement [I12, X02], diseased cells detection [N01] etc.

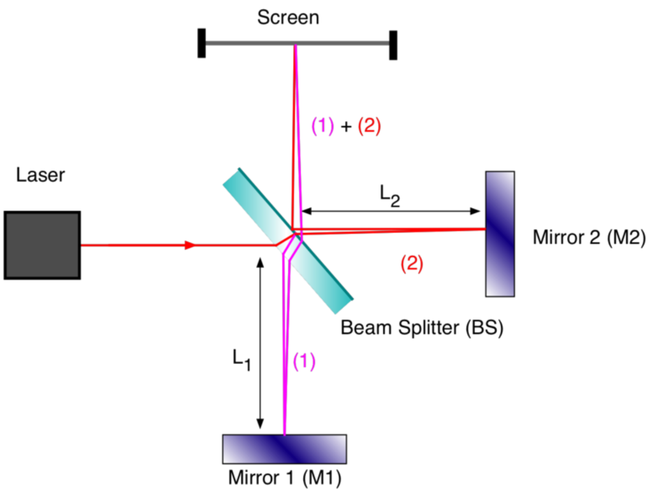



Fig. 2.18. Michelson interferometer set-up

Since Michelson demonstrated the first concept of interferometer by means of mirrors, a white light source, a compensation glass and a beam splitter (half-silvered mirror), countless interferometry principles, procedures and set-ups were developed. The linear set-up of a Michelson interferometer is depicted in Fig. 2.18. The laser beam is split and directed towards two mirrors that return the beams to the splitter and further they are reunited to the screen.

The output of this light travel is entitled interference fringes, meaning light sinusoidal intensity variation. In the Michelson's interferometer, if the distance between the beam splitter and one of the mirrors changes its value, Haidinger fringes (Fig. 2.19, (a)) appear on the screen, while if one of the mirrors slightly changes it is angle to the beam splitter, the result to be interpreted will be consisting of Fizeau fringes (Fig. 2.19, (b)) [M06].

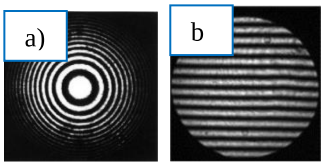


Fig. 2.19. Interference fringes: a) Haidinger fringes [S09]; b) Fizeau fringes [K06]

2.3.4. Uncertainty sources in laser measurements

Laser interferometry measurements uncertainty is mostly determined by the environmental errors (wavelength and thermal errors) and geometric errors (dead path, cosine and Abbe errors), as noted in the further equations [L05]:

$$e = L\,x\,(1 + \alpha\theta) - L_{LI} + e_{cos} + e_{DeadPath} + e_{Abbe} \tag{2.8}$$

$$u_{tot}^2 = \sum_i (u_i\,x\,c_i)^2 \tag{2.9}$$

where: $u_i$ is standard uncertainty; $c_i$ – sensitivity coefficient; $u_i\,x\,c_i$ – standard uncertainty contribution; L – measured probe displacement; $e_{Abbe}$ – Abbe error; α – temperature expansion coefficient of the stage; θ – temperature deviation from 20°C; $L_{LI}$ – laser interferometer measured distance; $e_{cos}$ – cosine error; $e_{DeadPath}$ – dead path error; $u_{tot}$ – total standard uncertainty.

2.3.5. Laser interferometers for machine tools control and calibration

A typical set-up for the calibration of a machine tool (Fig. 2.29) consists of a beam source, beam splitter(s), mirrors, a receptor, a support for the beam source (tripod), optic mounting kits and specific software. According to the measurement type, other supports, optic elements, environmental sensors and a compensator unit might be necessary. However, this set-up can be problematic because one of the optics is usually mounted on the main spindle. The intersection of the machine's movement axes limits the measuring capabilities by decreasing the measurable area.

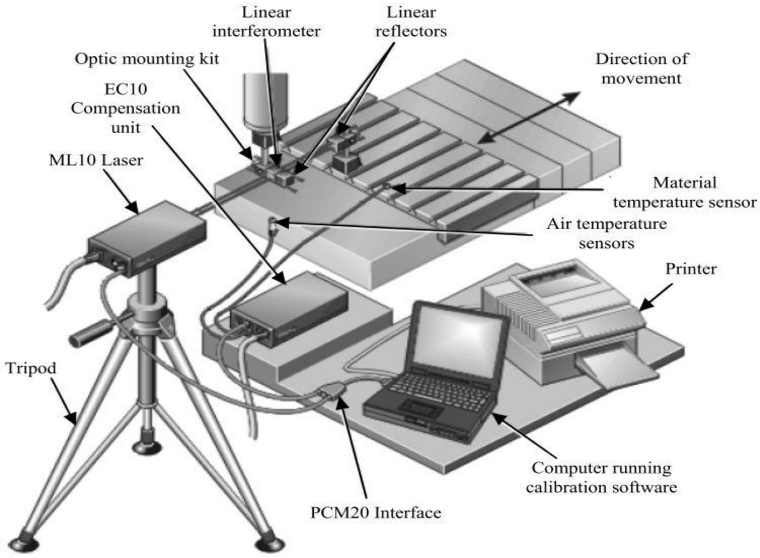


Fig. 2.29. Common set-up of an interferometer for a linear measurement [B12]

Interferometers are widely used for calibration due to their high accuracy and reliability [L08] and are able to perform measurements of linear and angular positioning, straightness, flatness, squareness and parallelism. It is important to mention that, although interferometry is well appreciated in all of these applications, each of them has to be made with specific optical components, the whole set-up procedure and realignment of the laser beam being time consuming. Furthermore, as previously mentioned, the set-up of the optical elements might determine the measuring range to not cover the whole length of the evaluated axis.

### 2.3.6. Grippers and mounting kits available on the market for interferometers

The marketed interferometers are commonly accompanied by a mounting kit that provides the connection between the optics and the machine tools. The kit aims to allow an interchange ability for the optic parts with no beam realignment.

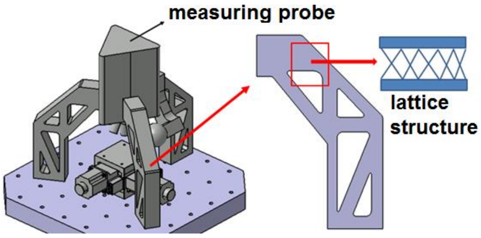
For instance, the Renishaw interferometer is equipped with mounting pillars, adaptors, base plates, clamp blocks and screws as presented in Fig. 2.38. The mounting pillars are designed to be screwed to a magnetic base while the clamp blocks ensure the connection between the magnetic base and the optic elements.
As manufacturers stated, the basic metallic parts (pillars/ columns and plates/ bases) are made out of magnetic or non-magnetic stainless steel [D03, R10].


Fig. 2.38. Optics mounting kit of Renishaw interferometer

### 2.3.7. Additive manufacturing of grippers and mounting parts

The additive manufacturing technology progress determined an increasing interest for lattice structures which are considered to be light-weight and offer control of flexibility. They began being used in different fields such as biomedical, aerospace and auto and continue being studied for various other industries. Some of the technical features were determined through the studies performed for cellular materials in previous decades, but the characteristics of lattice structures are still being researched due to their versatility.

In recent times, lattice structures began to be introduced in the construction of clamping and mounting systems and grippers, such as the systems presented in Fig. 2.40.




a)


b)

Fig. 2.40. Lattice structures within: a) fixing parts [E03]: b) robotic gripper [T09]

The main characteristic of lattice structures is that in the majority of cases, the only manufacturing method possible is 3D printing.
In order to be 3D printed, the parts containing lattice structures are digitally generated by means of different CAD software. Solidworks, Inventor and CATIA are virtual tools for building and designing from square one the lattice cells. It is then usually multiplied and subjected to a FEM analysis. Other software, such as Ansys, have started implementing modules which offer the possibility of generating pre-existing lattice structures (Fig. 2.41) in designated areas of the part/assembly.

Thus far, several characteristics have been determined for some widely known lattice structures such as cubic, diamond and octet [M09, D04, L11].

Since 2019, Ansys programme provides the possibility of lattice topological optimization, which enables anisotropic distribution of lattice construction thus being able to approach the models in nature, found in bones, wings, leaves etc. (Fig. 2.42).

In nature, these lattice structures are the results of evolution, where different parts have adapted to the specific loads that they were to carry, while also respecting geometry constraints. The lattice unit cell dimension, its strut height and thickness, and the density distribution are therefore built according to the fixtures, loads and material characteristics.

In terms of materials used for fabricating metrological parts, including specific supports, Invar is the most recommended material, due to its thermal stability up to a temperature above 100° C (see Table 2.2), but stainless-steel material is frequently used for mounting and gripping elements in metrology [D03, R10, D05, A07]. The Elastic modulus, being considerably higher, resulting in more rigid structures, makes stainless steel more suitable for these types of application. A similar material to stainless steel is Inconel, which is known to be having better corrosion resistance and thermal stability; however, it is more expensive.

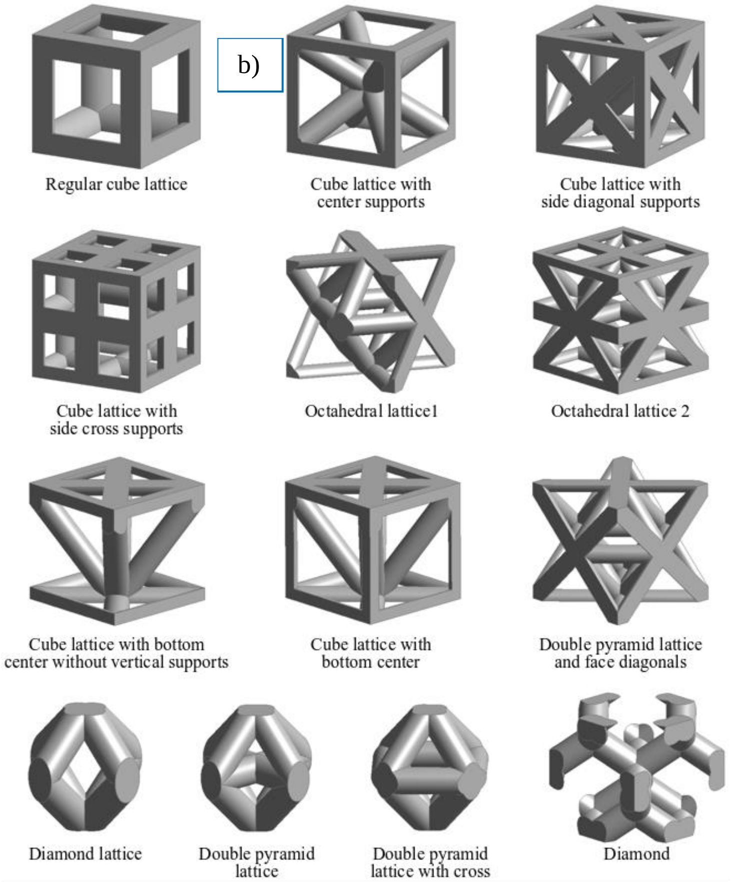



Fig. 2.41. Lattice structures: b) Available lattice cells in ANSYS 2021 R1 programme

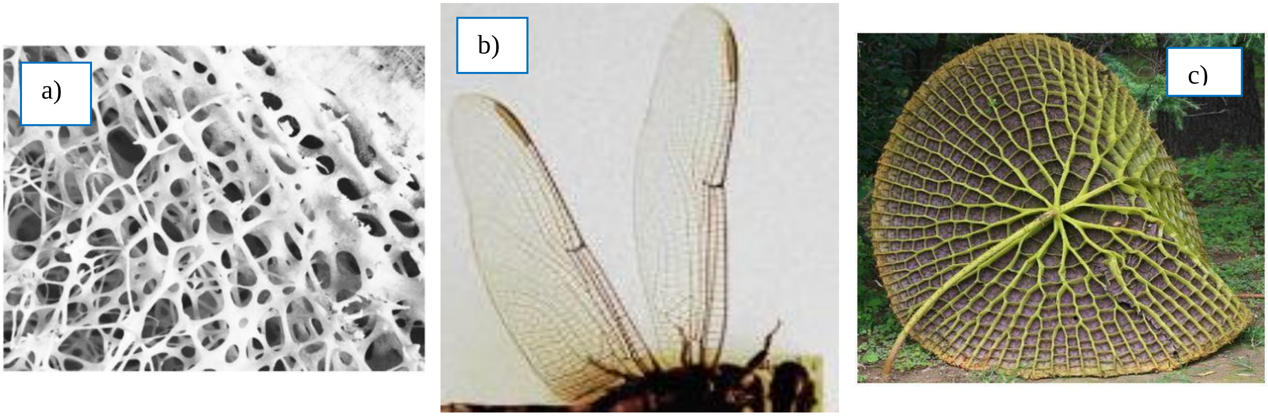



Fig. 2.42. Lattice structures found in nature:
a) bone structure [N02]; b) insect wings [W06]; c) leaf ribs [W06]

Another plausible material for manufacturing is considered to be aluminium alloy, due to low costs and weight, and easy manufacture. However, in metrology, alloys consisting mainly of aluminium are usually avoided due to a generally high thermal expansion coefficient and low rigidity, as seen in Table 2.2. Rigidity or specific stiffness, $K_s$, is [A08]:

$$K_s = E/\rho \tag{2.16}$$

where: E is elastic modulus (tensile modulus or Young modulus), and ρ - density.

Table 2.2. Characteristics of several materials for additive manufacturing

| Material name | Thermal expansion coefficient [$10^{-6}$ m/(m °C)] | Elastic modulus [GPa] | Density [g/cm$^3$] | Reference |
|---|---|---|---|---|
| FeNi36 | 1.2 | 137 | 8.1 | [A10] |
| 316L Stainless steel | 16.3 | 193 | 8 | [A11] |
| AlSi10Mg | 20 | 70 | 2.67 | [E04] |
| Inconel 718 | 12.8 | 205 | 8.22 | [H04] |
| TiAl6V4 | 9 | 110 | 4.43 | [E05] |
| CoCrSP2 superalloy | 13.6 | 200 | 8.3 | [E06] |

Notwithstanding, Al is commonly used in Ti based alloys for bone implants in human. With a similar rigidity to Stainless steel, but a better thermal stability and being biocompatible, the Ti alloys meet the requirements for bone replacement surgeries in almost any area of the body. CoCrSP2 is also biocompatible, but it frequently serves to dental implants.

Taking into consideration the rigidity of the materials listed in Table 2.2, it can be deduced that 316 L Stainless steel, Inconel 718, TiAl6V4 and CoCrSP2 superalloy are similar. However, the thermal expansion coefficient characteristics show a better behaviour for the last three of them.

# *Chapter* 3. Conclusions regarding the state of the art on measuring processes and systems

From the analysis of the actual state of the art on measuring processes and systems, important conclusions can be drawn, as follows.

• Metrology is characterized by a variety of definitions, but it may be resumed as the study of measurements. It is a branch of science with its main parts: theoretical metrology, such as accuracy of measuring instruments, measurement theory, assurance for unity of measurements and fundamental concepts; particular metrology such as length, time, electric quantities, mechanical quantities, light, velocity, etc.; applied metrology, such as control and calibration of measuring instruments, certification of standard specimens, etc. (see § 1.1).

Various factors may interfere in a production and measuring system therefore, in order to provide compliant products, an entire process that evaluates and corrects eventual errors was developed and it is found in the literature as quality control. An important segment of quality control is referring to measurements which are usually carried out by means of norms and standards. Standards may be from a shop floor level to the national/international level and they usually focus on specific areas of inspection, calibration, work operations, etc. The standards assure traceability; therefore, each country adheres to a specific standardization organization. ASRO is a member of the European organizations CEN, CENELEC, ETSI and of the international organisations ISO and IEC (see § 1.1).

• The measurand characteristics are some of the most important aspects when choosing a measuring method. According to this, the measuring methods are divided as direct method, indirect method, differential method, ratio method, reciprocity method, substitution method and transfer method. However, a perfect measuring device does not exist and therefore aspects such as the measurement scope must be taken into account in order to reduce the errors and uncertainties up to the acceptable levels (see § 1.1.1).

• The measurement errors, which are always present in the measured quantity, are split between the device errors, the methodological errors, the human errors and the statistics. The result of the measurement is the sum of the true value, the systematic errors and the random errors. Systematic errors refer to the accuracy of the measurement, while random errors concern the precision of the measurement results. The measurement uncertainty is a characteristic of the result, and it reflects the repeatability of the measurement and its reproducibility (see § 1.1.2).

• The inspection of production and measuring equipment refers to the process of directly or indirectly evaluating by measurements the elements that from the system. The inspection procedure is usually performed according to certified guidelines, but the equipment manufacturer or the user tend to intervene with specific needs according to the device or the client's needs (see § 1.2).

After each inspection procedure, an inspection certificate is issued by the operator or the inspector. This offers an overview of the products rejected, corrected and accepted and facilitate further improvement. The measuring instrument chosen for the inspection must be calibrated with an instrument 10 times more precise (see § 1.2).

Even though the statistical inspection is still used for mass production, lately new inspection principles have been developed, such as flexible inspection system and on-machine inspections (see § 1.2).

• The calibration process refers to the entire procedure of evaluating a device, instrument or equipment in order to improve its accuracy. The calibration certificate is issued by an authorized person, and it depends on external factors such as usage and environmental conditions (see § 1.3).

The traceability of a measuring device has a crucial importance, and it is reached by following the guides of international standards of calibration (see § 1.3).

• Any external factors variation from the standard procedure should be noted in the procedure reports. They may influence the final result and therefore they have to be monitored, controlled and recorded. Although usually the production and measuring environment cannot be entirely controlled, the accuracy and repeatability of the machines depend on it. Correction coefficients are applied in order to compensate the errors (see § 1.4).

• Temperature fluctuations are one of the most affecting environmental conditions. Punctual measurements with thermocouples, interferometers and infrared thermography are some of the measuring techniques used to identify heat sources since the temperature variations may contract or expand the materials of both the measuring equipment and the measurand.

The expansion coefficient of materials is the one that determines its stability along temperature variations therefore manifold standards suggests 20 °C as an optimal temperature for measurements. One of the steadiest materials at temperatures up to over 100° C is Invar (see § 1.5).

• Measuring instruments establish quantities or variables with respect to national and/or international standards (see § 2.1).

• The measuring instruments have various classifications, some of them being based on the output results, on the input data or precision (see § 2.2).

• The output results-based divides the measuring instruments into analogue, digital, display, recording, summing and integrated devices (see § 2.2.1).

• The input data splits the measuring devices into mechanical, electric, thermal, magnetic, optic and acoustic devices (see § 2.2.2).

• The classification based on precision, groups the devices into precision classes. Some of the most precise measuring devices are interferometers, autocollimators, electronic levers, reference encoders, etc. and they are usually required for production or measuring equipment calibration (see § 2.2.3).

• Interferometry was implemented in measurement procedures for the first time two centuries ago by Albert Michelson and it is up to this date considered one of the most accurate measurement devices, having steep precision, great compliance, high measuring speed and being a non-contact measurement (see § 2.3).

• Interferometry developed starting from the light wave's theories. Each wave is characterized by irradiance, phase angle, direction of propagation, wavelength, and direction of polarization. The beam intensity or its capacity to concentrate energy on a certain area during a limited amount of time is also known as irradiance. The angle determined by the displacement of a sinusoidal wave from a determined reference gives the phase angle. While the definition of direction of propagation is intuitive, when two waves have their only difference the direction of propagation, they create a pattern interference through their superimposition.

Wavelength is the length between the beginning and the end points of an oscillation cycle. Accuracy and repeatability of the interferometric measurements are, among others, given by the wavelength stabilization mechanism of the laser source. During an interferometric measurement, fringes are captured as outputs and its disturbance determines a displacement.

Since interferometry is based on a laser wave light wave emission for measurements, it may involve the Doppler Effect in various determinations, such as establishing the velocity of a moving target.

The direction of polarization is defined by the transverse direction of the electric field, and it can be either clockwise polarized or counterclockwise polarized (see § 2.3.1).

• The interferometry procedure requires two originally similar laser beams. In order to acquire them, one of the most used methods is by splitting the laser source beam through wavefront or amplitude division.

The wavefront division is achieved by means of screens with pinholes, mirrors, biprisms or lenses redirecting and dividing the light of a monochromatic point source to a common volume space where the beams create interference fringes through overlapping. Some of the most common wavefront division set-ups are the "Young's Double-Slit Experiment", Fresnel's biprisms, Fresnel's mirror, Billet's split lens and Lloyd's mirror.

The amplitude division is met when two or more light waves are obtained from the same wavefront. Through their recombination is achieved interferometry. Some of the most usual interferometric devices contain an amplitude division element such as beam splitters, diffraction graters or polarization prisms (see § 2.3.2).

• Various interferometers were developed along the time since Michaelson's interferometric set-up based on a white light directed through a beam splitter towards two different mirrors that redirect the beams towards a screen.

The Fizeau interferometer uses a laser source, a beam splitter, a camera and a reference surface in order to characterize an optical surface that only needs to be able to produce a clear interference pattern. In certain situations, the measuring may be captured simply by the eye of the operator.

In optical telecommunications and quantum mechanics applications, the Mach-Zehnder interferometer is manly used. It uses one light source, one detector, two mirrors and two beam splitters. Usually, the four optical elements are placed at a 45° angle as against the propagation direction.

The Sagnac interferometer is particularly stable and consists of the interference of two opposite direction beams directed by one beam splitter and two or more mirrors. It is particularly used in navigation and surveying systems, since it is designed to detect rotation.

Starting from Michaelson's interferometer, Rayleigh developed a model based on wavefront division method, producing two beam paths through two lenses, gas cells and compensators. It is used in various applications, from determination of the refractive indices of gasses to molecular weight measurements.

The Laser Tracker interferometer was firstly designed in 1985 and it was developed along the time to be used for CNC machines and MMCs volumetric calibration. The geometric errors are identified after at least 4 different positions of the laser source measurements where the reflector is tracked by the beam along a defined route (see § 2.3.3).

• Interferometry's measurement uncertainty is influenced by the environmental, geometric and other errors. The environmental errors depend on the light wavelength sensibility and the thermal expansion coefficients of the engaged materials. A wavelength compensation number is used to avoid the light wavelength error, while, for a minimum thermal error, a steady temperature and a pre-process preparation is necessary.

Dead path error is a geometric error that is related to the environmental conditions, but it is defined by the distance between the beam splitter and the point zero of the measurement.

In order to avoid it, environmental conditions steadiness and a distance minimization between the beam splitter and the beginning point of the measurement are required. When the laser beam is not perfectly aligned to the machine axis to be measured, an angle is formed that generates the cosine error. A better alignment leads to a smaller cosine error.

Another angle that creates an error may be generated by the reflector inclination due to imperfect movement. This error is almost impossible to be estimated or avoided (see § 2.3.4).

• Interferometry has a multitude of applications and it reformed metrology. Its typical set-up involves a laser beam source, beam splitters, mirrors, optic mounting kits and other supports and optics depending on the measurement type.

Even though interferometric measurements can be time consuming due to its set ups, alignment and realignment procedures, it is still widely used for calibration as a result of its accuracy and reliability.

By the instrumentality of interferometry, various properties and errors of production and measuring machines may be determined regarding positioning, straightness, flatness, squareness and parallelism.

The linear positioning measurement has a dedicated standard that describes all the procedure. This measurement implies a beam splitter, two reflectors and, when needed, guiding mirrors. One of the reflectors is positioned on a moving along the axis component of the machine and the other one is used for the reference beam.

The current set-up usually implies that one of optics is mounted in the main spindle. This aspect may considerably limit the measurable area.

The angular positioning measurement evaluates the angular positioning accuracy of the components. For the angular positioning measurements along a linear axis, one angular splitter and one angular reflector are used as optical elements to perform the procedure of this measurement type. The angular reflector is positioned on a part that moves along the axis to be evaluated. The differences of the two laser beams that return from the angular reflector indicates the angular error.

The guideways of a machine tool are evaluated through straightness measurements. It involves an angle mirror and usually a Wollaston prism.

The specific deviations associated to tables and flat surfaces are identified with a flatness measurement that implies measurements along two axes. The optical elements have to follow a predefined trajectory, based on Moody method, Grid map method or Half-grid map method.

Squareness and parallelism measurements are a combination of the previous optical elements and specific optical, fixing and gripping elements. While squareness measurement evaluates the perpendicularity between two axes, with linear movement, parallelism measurement evaluates this position between either two linear axes designed to be co-axial or between the axes of two rotational heads (see § 2.3.5).

• The interferometer manufacturers usually provide a mounting and fixing kit according to its applications, being designed for interchangeability when possible. The metallic parts from the kit are made from magnetic or non-magnetic stainless steel (see § 2.3.6).

• Even though they are still being studied, lattice structures began being used in increasingly more domains and even in mounting and gripping systems. Additive manufacturing and Design programmes facilitate the conception and achievement of these structures. One of the best materials for mounting and fixing systems is Invar due to its thermal stability, but Inconel718, TiAl6V4 and CoCrSP2 superalloy are also good options due to their characteristics (see § 2.3.7).

# *Part II.*
# Contributions to defining and constructive development of laser interferometry systems structure

# *Chapter* 4. The directions, main objective and methodology of research and development on laser interferometry systems structure

## 4.1. Directions of research and development

Based on the data and conclusions drawn from the present state of the art analysis, it is assessed to be of perspective, for the laser interferometry systems, the research and development directions on:

- general structure and characteristics;
- interacting processes and analytical modelling;
- operational characteristics, in order to develop applications in active industrial environments;
- analysis of the lattice structure integration into measuring systems;
- specific databases.

## 4.2. The main objective of research and development activity

Taking into account the present state of the art and the above research and development directions, it is assumed as main objective of the present foremost research and development doctoral activity: **structure and attributes development of laser interferometry systems.**

## 4.3. Methodology of research and development

The research and development methodology are elaborated as a reference base for the achievement of the main objective of the present doctoral thesis, respectively, of the following chapters of the doctoral thesis, as well as for future research.

The structure of laser interferometry systems should be configured in correlation with characteristics of the measurements objective.

The current structure of the laser interferometry systems contains a holding system for the beam splitter assembly that obstructs the linear measurements capacity sometimes for more than 30% for machining centres.

Thus, an innovative structure of a laser interferometry system for linear position aims at providing full working space availability for measurements at similar precision.

An innovative structure of a laser interferometry system for linear position is to be conceptualized and, more specifically, research, detailed design, manufacture, testing and validation of an innovative splitter positioning device should be developed.

The innovative system should be able to be used for various types of laser interferometric systems and measurements. Therefore, testing and validation of the system simultaneously in different set-ups should be performed.

The main research and development stages should be as follows.

(A) Conceptualization of a new splitter positioning device

- Initial data analysis
- Minimum requirements determination
- Structure optimization conditions

The conceptualization starts from initial input of requirements and necessities. An elaborate analysis of the actual structure and attributes of laser interferometry systems must be accomplished in order to assure consideration of all design constraints.

The conceptualization should take into account, other than enlarging the measuring area, the materials choice due to its requirements and also, to consider the measuring procedures that can be performed by means of the new splitter positioning device. As it is well known, each measuring procedure requires different optical elements, so that, each of the linear, angular, rotational, etc. procedure should be closely analysed in order to understand their limits (see § 2.3.5).

There must be utilised the relevant results of the studies unrolled on the developed system devices.

The various types of measurands that are taken into account must be well determined and analysed.

Some of the most important elements to be established are:

- minimum dimension of functional space for the new holding element;
- evaluating of external loads;
- determination of the optimum holding area;
- configuring of the objective functions;
- determination of response constraints.

(B) Design of the splitter positioning device

In order to design a functional splitter positioning device, the concept has to be taken through the following steps:

- computer-aided design;
- finite element method analysis;
- structure optimization.

Starting from the conceptualization output, an initial iteration can be designed and finite element analysed. Various CAD systems can be used for this study part, such as SolidWorks, AutoCAD 3D, Catia or Ansys.

For the lattice structure optimization, an Ansys Topological Lattice Optimization Analysis can be performed. The geometry is to be built as an assembly in order to segregate the lattice area.

The assembly should be subjected to a static structural analyse prior to the structural optimisation. The optimized version of the part is given by the objective function and the response constraints that are to be chosen. The digital validation connects the initial data from the finite element analysis with the modified optimized structure and offers a similar analysis of the structure with the lattice structure acquired.

The topological optimization will be unrolled, as a structural optimization that adopts the material data, geometry and model from the static structural analysis and requests the objectives of this procedure along with the lattice type, density and cell size.

(C) Splitter positioning device manufacturing

For initial evaluation of the design, a polyamide fabrication can be completed due to its low production costs and high precision. This procedure and material do not require supports or a printing base. The procedure will consist of:

- pre-process: powder preparation, CAD model design, model orientation in virtual printing space and model slicing;
- manufacture: layer by layer selective laser sintering;
- post-process, as cooling, surface finishing through not sintered powder removal.

Depending on the final design, the SPD can be fabricated through conventional procedures or through additive manufacturing out of the chosen metal powder, function to characteristic's evaluation and its availability. The additive manufacturing process might require a more extensive preparation but it is more suitable for prototypes or single part fabrication.

The product design must be altered in order to fulfil particular additive manufacturing requirements. This manufacturing procedure will consist of:

- pre-process, as powder and printing base preparation, CAD model design according to additive manufacturing process requirements, model orientation in virtual printing space, supports generation and model slicing;
- manufacture, as layer by layer;
- post-process, as cooling, powder removal, stress relieving heat treatment, part removal from the printing base, supports removal from the part, surface polishing or grinding, hole and thread execution.

(D) Splitter positioning device validation

In order to assess the concept, design and manufacturing achievements, the new set-up for laser interferometry system is to be tested and validated.

Choosing the proper evaluation methods and conditions has a great impact over the reliability of this product.

Preliminary results can determine whether or not the new set-up results are to be taken into consideration. As a consequence, consecutive measurements with an existing set-up and the new set-up should be taken into consideration. This procedure offers the freedom of complete measurements for each set-up which fully examines their capabilities, while immediate measurement as recommended by the interferometer's manufacturer offers a reference base for the results.

A peer assessment of the two set-ups is given by measurements performed in parallel with two similar laser interferometry systems.

The environmental conditions have a significant influence over the interferometer's measuring results, so that, the measuring should be made in different working conditions.

The ISO 230-2 procedure, as an internationally approved method, is to be used in order to validate the results.

In summary, this methodology involves high tech procedures, some still in the development stage - lattice optimizations, 3D printing -, which require continuous testing during the various phases of product development. Equally, the development procedure does not present possibilities of simplification at the current stage of research but, once a first set of data is obtained, it is possible to follow the elimination of some steps, such as preliminary printing on plastic, or such intense experimental validation, etc.

# *Chapter* 5. Structure and characteristics development of laser interferometry systems

The development of structure and characteristics of laser interferometry systems, including the author's published elements [G04], is as follows.

The present proposed structure and characteristics of laser interferometric systems are developed at high level of generality, open to particularizations, in context, as well to other description levels.

Let measurement object be a set, $G$, of geometric entities, $G_i, i = \overline{1, n}$,

$$G = \{G_i | i = \overline{1, n}\} <=> G = G_1 \cup G_2 \cup \ldots \cup G_i \cup \ldots \cup G_n \tag{5.1}$$

It is to underline that each geometric entity $G_i$ is well-defined by the specific features - nominal characteristic, tolerance field, reference elements/ coordinate systems.

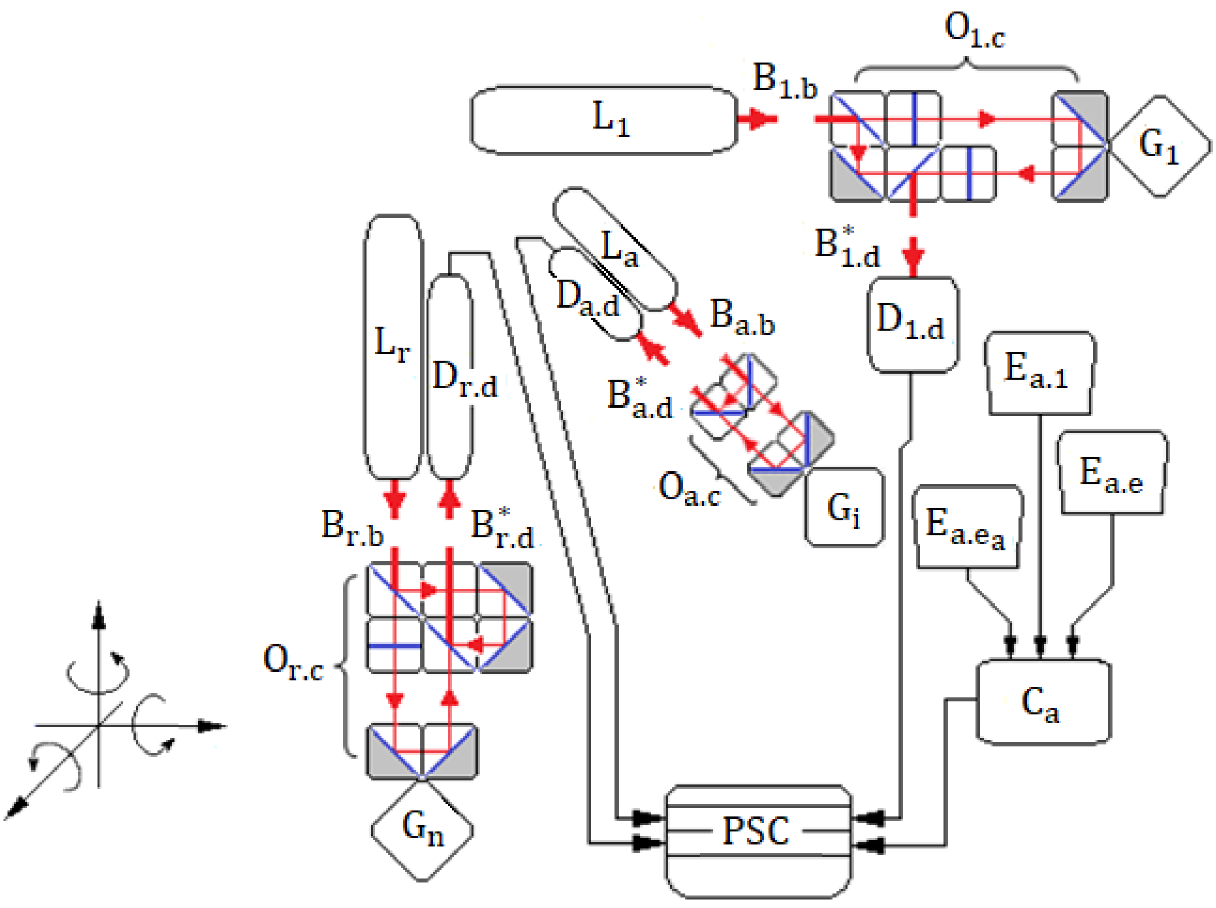



Fig. 5.1. A general structure of a laser interferometric system

The laser interferometric system, LIS, for measurements upon the geometric group G ($G = \{G_i | i = \overline{1,n}\}$), is structured so that to include elements as coordinate system ($CS_j, j = \overline{1,m}$), laser sources ($L_a$, $a = \overline{1,r}$), laser beams ($B_a$, $a = \overline{1,r}$), optical modules ($O_a$, $a = \overline{1,r}$), output beams ($B_a^*$, $a = \overline{1,r}$), detectors ($D_a$, $a = \overline{1,r}$), environmental sensors ($E_a$, $a = \overline{1,r}$) and compensation modules ($C_a$, $a = \overline{1,r}$), process software and computers, etc. as presented in Fig. 5.1.

The real constructive structure and characteristics of LIS depend on the measurement object features and other techno-economic conditions.

Thus, a *laser source* element and a *detector* (*receiver*) element are distinct system components or - incorporated together in a *laser unit* component, optical elements type *beam splitter* and *interferometer* are distinct or - incorporated together in a *beam splitter*, some *environmental sensors* are included in a *compensation module*, etc.

# *Chapter* 6. Development of an innovative laser interferometry system for linear position

The development of an innovative system for interferometric measurements, including the author's published elements [M09, M13, O01, S14], is as follows.

The optical elements of laser interferometry systems are, typically, fixed with magnetic V-blocks to the main parts of the machine tool, as seen in Fig. 6.1. The laser head, which is also the beam source and the signal receptor, is situated at a $D_1$ distance to the beam splitter assembly that is fixed through a magnetic V-block to the main spindle. The distance $D_2$ between the beam splitter and the retroreflector marks a safety distance between the two components to avoid collision. The retroreflector is connected through another magnetic V-block to the working table. From that point on, starts the measuring area ($D_3$) that ends at the travel limit of the working table on the linear guides on Y axis. In the particular case study with a Makino D200Z 5-axis vertical machining centre, the working table has a travel range of [-170, +130] mm, on Y-axis. The spindle, that has two linear guides, is able to travel on X and Z axes and intersects the working table in an area around the 0 point of the Y-axis.

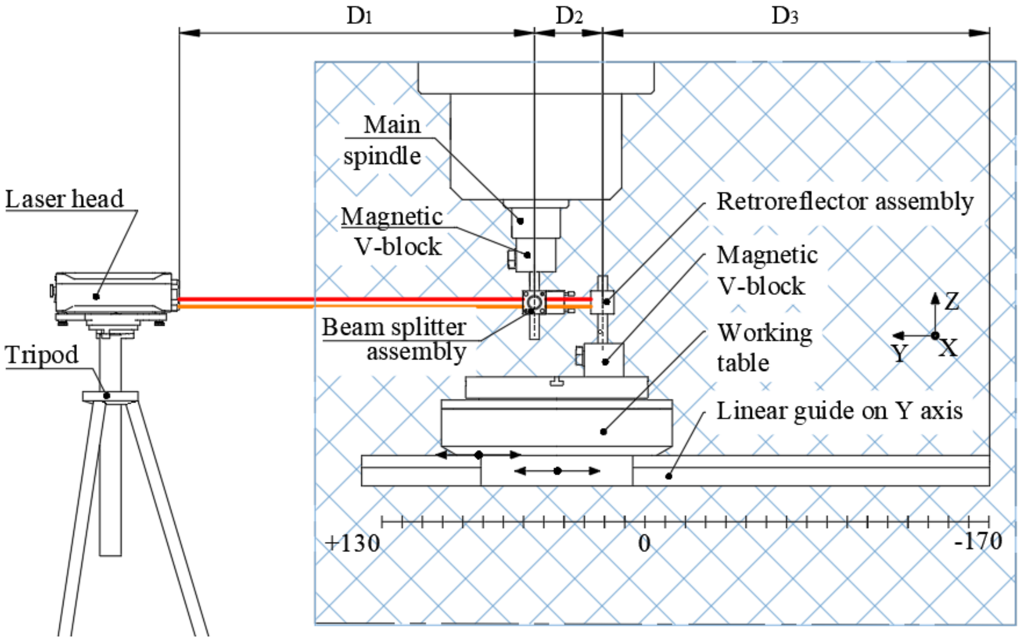



Fig. 6.1. Regular set-up for a linear interferometric measurement on a CNC vertical machining centre

In a system structure as represented in Fig. 6.1, $D_3$ is limited to around 60% of the working table travel.

The main purpose of this development would be to enable the interferometric measurement of the whole working area.

In order to be able to access the whole working area of the axis travel, the new structure of laser interferometry systems is developed so that the beam splitter and retroreflector would not be gripped to elements whose axes intersect.

The two set-ups have a main difference which consists in the position of the beam splitter assembly.

The new structure gives the operator the possibility to evaluate the whole working area of the Y axis, fact that can be vital in machining centres to determine clearances and precision.

The general characteristics of a device that allows interferometric measure of the whole working area, SPD, should be:

• minimum mass;
• high rigidity (low compliance), related to the action of its weight and the weight of the supported parts (optical and additional elements);
• simple and reliable interlocking within a laser interferometry system.

Evaluating two of the commercial laser interferometry systems [R09, R10, D03], (§ 2.3.6), the dimensional characteristics required for the considered device have been determined.

The supported parts have a total mass of 560 g. To ensure a rigidity of SPD of high value, a calculus (pressure) force of 15 N was chosen, which is related to a mass of approximately 1.5 kg.

The rigidity is influenced by the material characteristics, so that several studies were performed to determine the type of material and lattice structure that can be used [M09, M13, S14, O01] (also, see § 2.3.7).

The splitter positioning device, SPD, is developed as 2 main different constructive types.

The finite element analysis of the steel part reveals a good rigidity having micrometric displacement, but its considerable mass of around 2.1 kg, and manufacturing challenges opens the path for further improvements.

The effective structure has been generated and multiplied using SolidWorks [D06] part features.

For coarse fittings and analysis, the finished part is subjected to a FEA and, thereafter, it is SLS fabricated out of PA2200 with EOS FORMIGA P110 additive manufacturing mechanism. The polyamide material PA2200 is chosen for this prototype, because it is a much cheaper and faster procedure compared to the metal additive fabrication.

A visual inspection indicates a small gap generated, most probably by incorrect handling; therefore, it can be taken into consideration that the current outer areas of structure are sensitive and easily deformable.

A further iteration of the device is corner rounded, in order to prevent deformation. The bottom of the structure is designed at the same level so that it can be placed on the metal printing plate without additional supports and for ease of removal from the support plate.

The specific parts of the device are SLS manufactured out of polyamide material PA2200 and subjected to testing in order to assess its applicability. An experimental testing on the prototype shows that the measurement range is significantly large (300 mm) in the measurements using the new device, comparing to the measurements without it. This important result reveals the utility of the splitter positioning device to enlarge the measurement area to the entire working area of the CNC centre. But, in the same time, the *errors*, generated because of the polyamide material in the constructive structure of the new device, are of high values, not acceptable, therefore, the next developments must take into consideration these elements.

Another iteration of the device is developed with its central body of lattice structure, corner rounded, and its dimensions were decreased as much as possible, using the advantages offered by the direct metal laser sintering process.

The DMLS process involves particular attention to the part details such as holes, edges, overhangs and base, therefore, the part is adjusted, with tear drop shape holes, angles optimization, same level base plan, no overhangs and material consumption minimization.

The positioning tuning system area undergoes specific changes

In order to avoid a possible misalignment caused by the structure deformation, a push system with two screws is designed to adjust the small angle movements.

The lattice generation is made by means of the Ansys [A12] lattice topological optimization module, taking into consideration the FEA output, the objective function and response constraints of interest, and the influential aspect that printed part should allow elimination of the loose powder (no embedded powder volumes).

The yielding of the part can be disregarded as it results from the von-Misses stress analysis. The stress differences between the two parts (full body and lattice body) were almost unchanged and the tension level is low enough that it does not need to be considered.

For this study, the cell dimension was of 5 mm. The optimization objective was minimization mass and compliance.

The density range was chosen in order to avoid embedded powder volumes and to not reach the minimum manufacturing size.

The body geometry to be optimized generated a high lattice density closer to the tripod grip and a low density at the other extremity.

Ansys produces an equivalent density map through this optimization therefore, the final step of the structural optimization resumes the previous static structural FEA but with the new geometry. The displacement differences between the two are micrometric.

Another iteration of the new device contains elements that allows the beam-to-beam splitter alignment, without the position tunning system.

In connection with the metal printing of the specific components of the device and DMLS fabrication process, printing supports of about 4 mm were added to the orientation holes and to the overall part in order to facilitate the wire cutting part removal from the printing plate during post DMLS process.

For this final geometry and the CoCr material, the Ansys programme determined an expected mass of approximately 500 grams, with almost 25 % less than the full body part, but at the same time, with 76% less than the mass of the first iteration. The percentage can change according to the density range, lattice cell dimensions, external loads and initial geometries.

For the pre-processing of the part, which is prior to the fabrication of the specific components of the device, the CAD assembly is exported to .stl format for additional part editing, support addition, problematic areas detection and machine definition in Magics [M14] programme. The parts are then exported as a cli. extension for the EPHatch [E07] programme to be sliced. In this case, the parts were sliced with a 0.03 mm increment, thus defining each of the 1566 layers to be printed. When the final parts are prepared, they are transferred to the printing equipment with an .epi extension.

The printing equipment used in this fabrication is a Shining 3D EP M250 3D model. Prior to the fabrication beginning, the powder is sieved, dried and deposited into the feed cartridge.

The additive manufacturing of the specific parts of the device would last under normal conditions for around 34 hours. In this particular case, the printing procedure finished after 240 hours, due to unknown cause.

During the post-processing procedure, after additive manufacturing, a cooling time is required before the building platform extraction. Afterwards, the powder is carefully removed from all the building platform and parts areas.

The building platform is then removed and introduced in the sanding machine to smooth the surfaces and blow the remaining embedded powder.

The following step involves the stress relieving process. The powder manufacturer recommends a stress relieving procedure into the furnace, under argon atmosphere. The available equipment did not offer a controlled atmosphere option, therefore an adaptation of this procedure to non-controlled atmosphere was determined. The parts are initially heated up to 450°C for an hour, the temperature is maintained there for an hour, and then it is raised up to 800°C for one hour and it is maintained there for another one hour. Afterwards, the heat is turned off and the cooling process comes naturally.

After the relieving process, the material hardness may be determined. In this case, the parts capacity to resist deformation is of 44,5 HRC. This result falls within the margin estimated by the powder manufacturer, with their recommended stress relieving procedure.

The following steps regard parts extraction from the building platform and the needed machining after the printing. The parts extraction is made by means of wire electrical discharge machining.

The resulted parts are then post processed to remove sharp edges and the remaining supports. Several surfaces of the splitter support are grinded according to the requirements. Also, applying EDM procedures, the cylindrical hole and the associated thread were machined with specific electrodes.

# *Chapter* 7. Validation of the new splitter positioning device within laser interferometry systems for linear position

The validation of the new splitter positioning device within laser interferometry systems for linear position, including the author's published elements [A04, S15], is as follows.

## 7.1. Experimental protocol and environmental conditions

As presented in the previous chapters, performing linear measurements with laser interferometry systems offers reliability and high accuracy but it also has certain constraints. One such constraint is determined by the placement of the optical elements, which requires a rigid metal area for the magnetic V-block. It often leads to a limitation of the measuring range for all the machining centres.

### 7.1.1. Experimental protocol

SPD is to be tested on three CNC centres, CNC Makino D200Z 5-axis machining centre, CNC Spinner VC1020 machining centre and CNC Spinner MC1020 machining centre.

During each test, two major laser interferometry systems, LISs, are configured and used, consecutively or in parallel (simultaneously), i.e.:
- a simple (regular) laser interferometry system "simple LIS",
- a laser interferometry system including SPD "LIS including SPD".

The considered LISs are structured with elements from Renishaw XL-80 laser systems.

The measurements procedure to be used is based on the elements described by ISO 230-2.

The environmental conditions for the measurements must be adapted to the equipment manufacturer's specifications. The standard suggests an optimal temperature of 20° C. But, even under this situation, errors can occur and therefore the temperature value must always be mentioned in the test report.

The considered procedure is to be used for consecutive and parallel measurements. Various comparative measurements are unrolled with labels as presented in Fig. 7.7.

The results are displayed in graphs where the measuring points coordinates (position distances) along the machines travel Y axis are represented on the abscissa, and the corresponding positioning errors – on the ordinate.

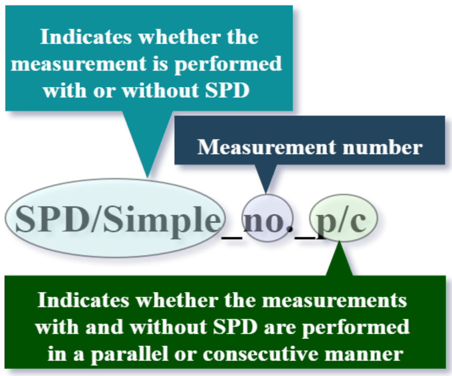



Fig. 7.7. Measurement nomenclature

### 7.1.2. Study on environmental conditions

The effects of LIS environmental compensation are put into perspective, through two types of tests: one with environmental compensation unit and one without it. Preliminary studies were performed to determine the thermal influence on interferometric measurements [A04]. However, as the manufacturer states [R10], the XC-80 compensator unit can compensate the environmental conditions influence.

Two standard measurements were performed on the CNC Makino D200Z 5-axis vertical machining centre, and the results are represented in Fig. 7.9. Along the abscissa, the Y axis specific range values are kept within [-170, +10] mm range.

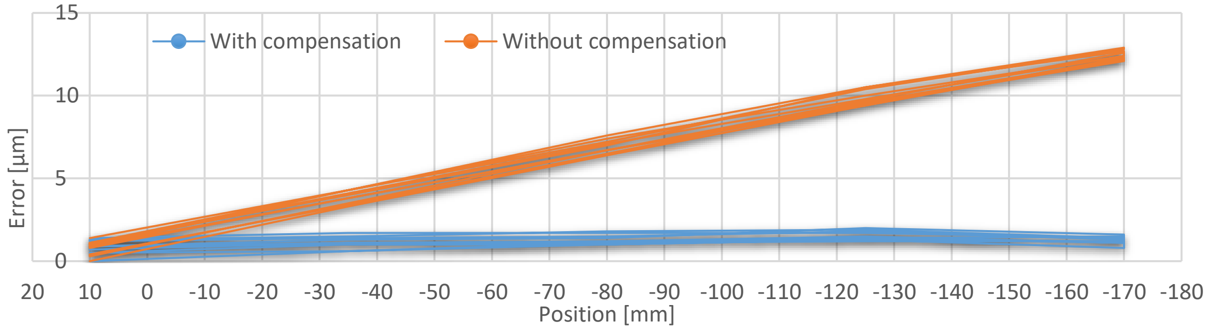



Fig. 7.9. Y axis accuracy and repeatability of positioning error during measurements with and without compensation

It is an obvious difference between the values given by the measurement with compensation, where the considered CNC centre reveals close to no positioning error, and the values given by the measurement without compensation, where the error goes up to over 12 µm.

The specific analysis statistical indicators show the followings:

• the positioning error, the systematic positioning error and the range of mean bidirectional positioning error are strongly influenced by the environmental conditions;

• the positioning repeatability is of an acceptable value (1.5 – 2.1 µm), in each measurement case.

It is to be mentioned that for the considered measurement cases, the environmental conditions varied with less than 0.5°C for the temperature, while the other conditions were stable.

### 7.2. Consecutive tests in laboratory conditions

The consecutive tests are referring to the use of the LIS including SPD and, consecutively, the simple LIS.

The CNC machining centre for these tests was the CNC D200Z 5-axis vertical machining centre.

The laboratory conditions were considered to be in a closed environment, with limited traffic. All the environmental conditions were noted, and the XC-80 compensator was enabled.

Several groups of Y axis accuracy and repeatability of positioning measurements were conducted. From these, three groups (with order number 02, 03 and 06) of results are presented in Fig. 7.10. The graphs show the positioning errors along the Y axis. Along the abscissa, the Y axis points coordinates are limited to a [-170, +10] mm range when the simple LIS is used (see § 7.1), while the Y axis points coordinates are in the extended range of [-170, +130] mm when the LIS including SPD is used.

It can be noticed that the measuring cycles start and end up at approximately 0 µm error, while along the evaluated Y axis (abscissa axis), it tends to increase. The SPD_02_c and the Simple_02_c measurements results have an increasing difference between similar points with a reach of about 4 µm at the comparative point of 10 mm position coordinate. The other two sets of measurements, even though they have different values from the previous ones, they keep the same difference of around 4 µm at the comparative point of 10 mm position coordinate.

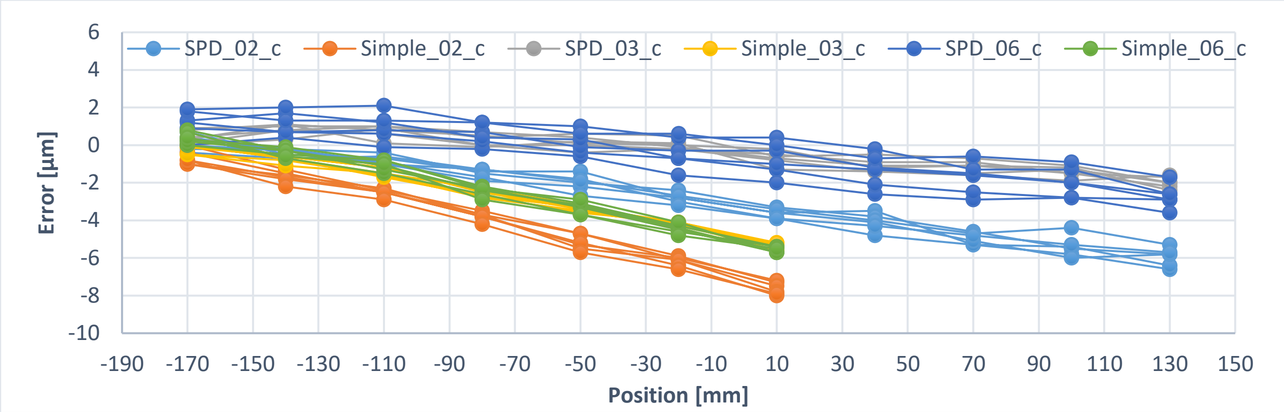



Fig. 7.10. Y axis accuracy and repeatability of positioning measurements during consecutive tests

The specific analysis statistical indicators show the followings:

• generally, the values of each analysis statistical indicator at the measurements with the LIS including SPD and with the simple LIS are of the same order of magnitude;

• the positioning error, the systematic positioning error and the range of mean bidirectional positioning error at the measurements with the LIS including SPD are smaller or very close to those from the measurements with the simple LIS; the positioning repeatability value is of 1.8 – 4.9 µm at measurements with the LIS including SPD, and of 1.1 - 2.1 µm at measurements with the simple LIS.

The environmental compensation corrected the measurement errors that might have happened due to the environmental conditions' variation influence over the materials involved in the procedure or the laser wave. Even though the procedures were performed in a closed chamber, with little to no traffic, and only one operator was present. The air and material temperatures were quite different even though the consecutive sets of measurements were performed with minimum time intervals. The overall variations between the beginning and the end of a set go even up to 2° C, which might have changed the wavelength and considerably influence the measurements' results. The difference between air and material temperature is almost 1° C for all the sets except the first one, where the biggest temperature variation is also captured. Altogether, the temperatures reach up to 26° C, representing a variation of up to 6° C to the ideal temperature value of 20° C, recommended by the standards.

Overall, these measurements prove the applicability of SPD. It is obvious that an innovative device to support the beam splitter, enlarges the measuring range making possible the evaluation of the whole axis travel. As determined, a whole area of around 40% of the axis travel was added to the measuring range, using a LIS including SPD.

### 7.3. Parallel tests in laboratory conditions

The parallel tests are referring to the use simultaneously one simple LIS and one LIS including SPD.

The main feature of the parallel tests is that both different LISs are functioning in the same technical conditions associated to the machine working elements and in the same environmental conditions.

The working conditions are identical or similar to those presented in the previous subchapter: CNC D200Z 5-axis vertical machining centre, the general structure of each laser interferometry system, environmental sensors, XC-80 compensator, etc.

In particular, the simple LIS and the LIS including SPD. were configured using the specific elements from two LISs of different editions type Renishaw XL-80 (Fig. 7.12).

The set-up was particularly meticulous to be put in place, since the two laser sources have to be close next to each other so that each laser beam to reach the correspondent reflector. The beams can be aligned on the same time or separately.

It is underlined that, because of the simple LIS structure, during the considered parallel tests, the Y axis points coordinates are limited to the [-170, +10] mm range.

Several groups of Y axis accuracy and repeatability of positioning measurements were conducted. From these, three groups (with order number 05, 11 and 13) of results are presented in Fig. 7.14.

The values keep the pattern from previous consecutive tests (see § 7.2) and have quite the same differences between them of about 4-5 µm at the maximum distance.

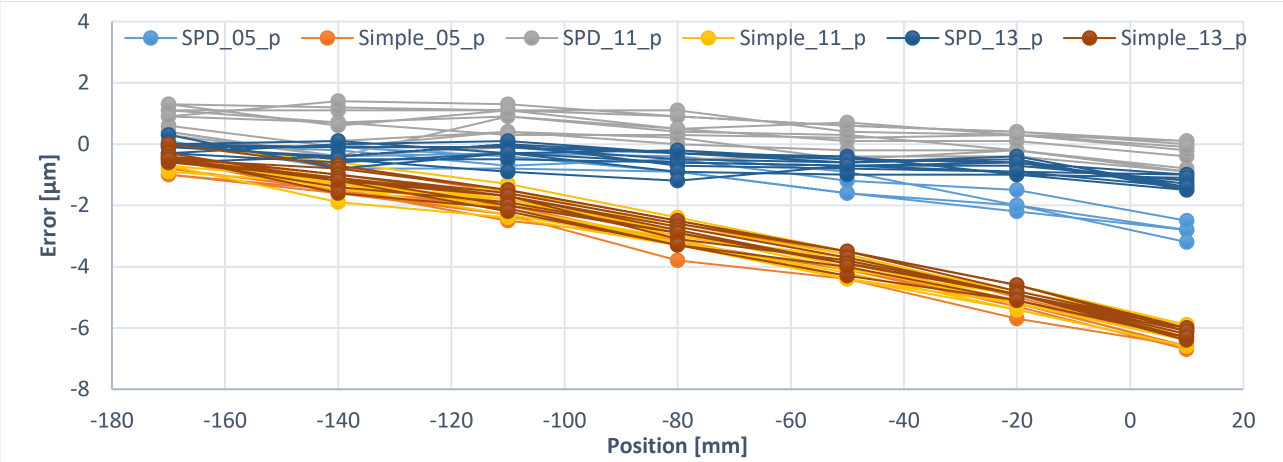



Fig. 7.14. Y axis accuracy and repeatability of positioning measurements during parallel tests

The specific analysis statistical indicators show the followings:

• generally, the values of each analysis statistical indicator associated to the LIS including SPD and to the simple LIS are of the same order of magnitude;

• the positioning error, the systematic positioning error and the range of mean bidirectional positioning error are smaller at measurements with the LIS including SPD, even 4 times smaller in some cases; the positioning repeatability value is of 1.1 – 3.4 µm at measurements with the LIS including SPD, and of 1 - 2.1 µm at measurements with the simple LIS.

The specific parameters were captured simultaneously by sensors of the two XC-80 compensation units. The parameters variations are not larger than 1° C at temperatures, 5.4 mbar at pressure and 7% at humidity, but if the XC-80 units would not implement the compensation, the wavelength would suffer changes.

### 7.4. Parallel tests in industrial conditions

The parallel tests in industrial conditions were performed on two different CNC machining centres, i,e., CNC Spinner VC 1020 machining centre - with table travel on axes X, Y and spindle travel on Z axis, as well as  CNC Spinner MC 1020 machining centre – with spindle trave on all X, Y, Z axes.

The other working conditions are similar to those from parallel tests in laboratory conditions (see § 7.3), i.e.:  simple LIS and the LIS including SPD were configured using the specific elements from two laser systems of different editions type Renishaw XL-80, both reflectors are placed on the same mounting pillar, etc.

(A) Parallel tests on CNC Spinner VC 1020 machining centre

It is to be noted that at CNC Spinner VC 1020 machining centre, the table Y axis working travel range is of 610 mm, while the maximum evaluated range was of about 480 mm because of the limit introduced by the simple LIS structure.

The results (Fig. 7.16) show a similar pattern, with a slight difference for the results associated to the LIS including SPD, of up to about maximum 15 μm. The errors are under 10 μm with small oscillations up until the point of 240 mm coordinate; from that point on, the error decreases until up to - 40 μm for the simple LIS, and until up to - 20 μm for the LIS including SPD. On the returning path, the values are slightly similar with a continuous difference of less than 10 μm between the errors associated to the considered LISs.

The range of mean bidirectional positioning errors is of around 30 μm for the LIS including SPD and of around 40 μm for the simple LIS. The positioning repeatability is slightly similar between the two LISs with a small variation for the LIS including SPD. Overall, the positioning errors met in Y axis evaluation proved to be higher in the second part of the travel axis which probably of the wear level of the linear guides in that working area of the machine.

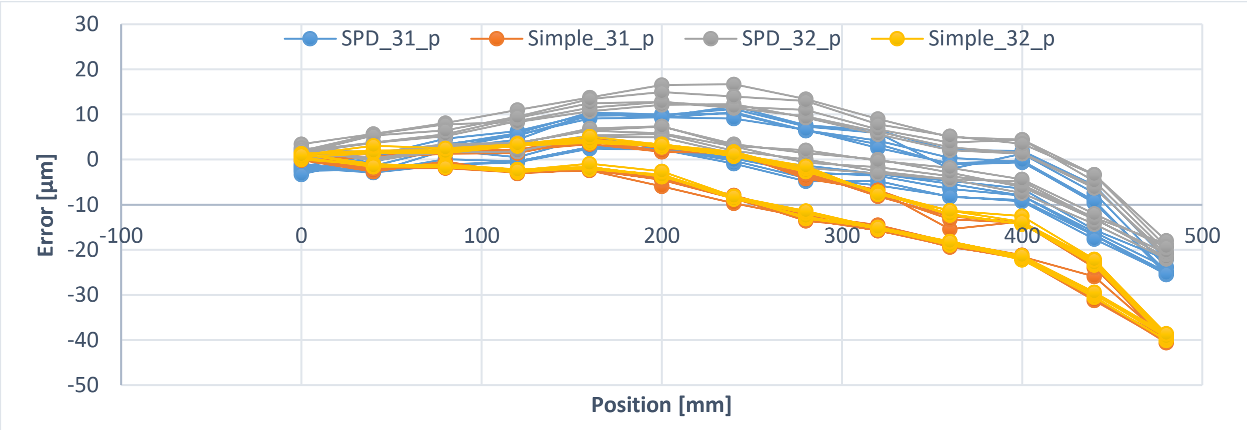



Fig. 7.16. Y axis accuracy and repeatability of positioning measurements during parallel tests on a CNC Spinner VC 1020 machining centre

The environmental conditions were stable. It can be noted that the difference between the air and the material temperature is about 2° C, simmilar to the laboratory onditions (see previous subchapter), but the overall temperature is higher than the recommended 20° C temperature, which indicates the need of the environmental compensator.

(B) Parallel tests on CNC Spinner MC 1020 machining centre

It is to be noted that at CNC Spinner MC 1020 machining centre, the spindle Y axis working travel range is of 580 mm, while the maximum evaluated range was of about 380 mm because of the limit introduced by the simple LIS structure.

The set-up for the simple LIS and LIS including SPD takes significant time and space.

The results follow a similar pattern of errors associated to the LIS including SPD and to the simple LIS, respectively, as presented in Fig. 7.19.

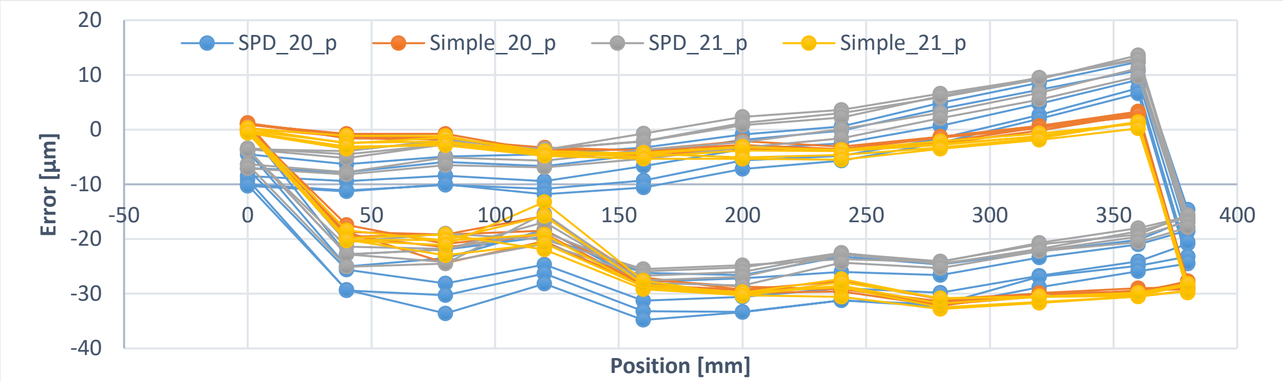



Fig. 7.19. Y axis accuracy and repeatability of positioning measurements during parallel tests on a CNC Spinner MC 1020 machining centre

The measurements start from the point of 0 coordinate of theY axis; at the position of 40 mm along the axis, the positioning error is - 20 µm. This error continues with small oscillations along the axis up to 120 mm position, where the error becomes -30 µm. The error with a very small decreasing continues up to the last value at 380 mm position. On the returning path, an abrupt error correction from around -30 µm to 0 µm is noticed. This is probably due to a clearance in the linear guides. From that point on, the returning points are within ±10 µm error around the null value.

The bidirectional positioning errors are at around 40 µm while the positioning repeatability is slightly better for the simple LIS. A maximum value variation of about 15 µm can be noted between the two different LISs.

As in the previous industrial parallel tests, the environmental conditions were stable.

The comparative measurements, presented in this chapter, show that SPD, included in a LIS, meets the specific requirements. The experimental results reveal important similarities between the measurements performed with the LIS including SPD and the simple LIS, leading to an enhancement of the capabilities of LISs to evaluate the entire possible travel on certain axes of CNC centres.

# *Chapter* 8. Final conclusions and main contributions regarding the structure and attributes development of laser interferometry systems

(1) From the analysis of the actual state of the art on measuring processes and systems, important conclusions have been drawn, as they are presented in the chapter 3.

(2) Based on the data and conclusions drawn from the present state of the art analysis, it has been assessed to be of perspective the research and development directions as presented in § 4.1.

(3) In relation to the present state of the art, as well as the research and development directions, it has been assumed as main objective of the foremost research and development doctoral activity (see § 4.2): structure and attributes development of laser interferometry systems.

(4) The relevant conclusions associated with the foremost research and development doctoral activity to achieve its main objective, guided by the methodological reference elements (see § 4.3), are as follows.

○ The development on general structure and characteristics of laser interferometry systems includes analytical descriptors and some general features referring to measurement object, coordinate system, lasers, laser beams, optics, output beams, detectors, environmental sensors and compensation modules, electronics, process software and computer(s), assembly, calibration and other elements (see § 5).

○ Due to the actual set-up of the optical elements, the laser interferometry systems for linear measurements are often restricted to a limited measuring area due to their placement inside the working area of the equipment. As an example, for a Makino D200Z 5-axis vertical machining centre, an evaluation of the positioning error of the Y axis can be performed on only around 60% of the working table travel. In order to overcome this limitation and to allow for a full range of measurement, a splitter positioning device, SPD, for laser interferometry system structures was developed as a new system component (see § 6. 1).

○ The general characteristics of SPD should be: minimum mass; high rigidity (low compliance), related to the action of its weight and the weight of the beam splitter assembly; simple and reliable interlocking within a laser interferometry system (see § 6. 2.1).

○ For the design phase, the load that the device was to bear was approximated to 15 N, taking into account its own weight and that of the parts involved. SPD should deform as little as possible under this load. The resulting rigidity of the component is a cumulated result of the part geometry, the fabrication method and material being used (see § 6.2.1).

○ SPD can be designed and manufactured in various forms and from different materials, but by taking into consideration the resulting mass and material homogeneity (see § 6.2.2).

The central part of the SPD body is analysed as solid, hollow or lattice form, made of metallic or polyamide material.

The load applied to SPD leads to bending induced deformation. In order to compensate for this inconvenience, a push system with two screws has been designed to adjust the small angle movements.

○ A SPD that integrates lattice structures obeys all design criteria, as it can be customized and its geometry can be optimized according requirements. The lattice structures, presently, can only be obtained by additive manufacturing. This implies adjusting the component design also in accordance with the fabrication type, since practice has shown that certain 3D printed geometries cannot faithfully follow the CAD design (see § 6.2.2).

○ A proper fabrication method might be of use for a concept first evaluation, to ensure the feasibility of the geometry. A polymer-based SPD was firstly fabricated, using a PA2200 powder and an SLS machine. By analysis the quality of fabrication, it was determined that rounder corners are more suitable, along with material use optimization and other design improvements prior to DMLS fabrication. The resulting polymer prototype was also considered for use in interferometric measurement but, as it exhibited a viscoelastic behaviour (continuous deformation under load), it did not respect the stiffness design criteria and was eliminated from further scrutiny.

○ The lattice structure can be integrated into the SPD main part, with identical cell characteristics or through an optimization procedure, by considering the cell lattice type and the optimization objectives. Commercially available FEA programs have started in the recent years to supply topological optimisation modules or algorithms. Ansys software was used for SPD structure optimisation using lattice cell structures, geometry in accordance with a set of optimisation parameters and design constraints (see § 6.2.2).

○ The DMLS fabrication method requires special adjustments of the geometry, such as tear drop shape for the holes, supports for overhangs or angle changes for some supports, etc. to ensure the absence of fabrication induced defects. Due to part possible thermal deformations, in order to assure the prescribed precision of the SPD surfaces, the flange and boss positioning surfaces are designed to be machined after the parts are additive manufactured (see § 6.2.2).

○ Material analysis has led to conclude that the most suited one for the current application is CoCrSP2 superalloy, supplied in a powder form. In terms of pre-processing of the fabrication phase, both the geometry and the alloy powder have led to a layer thickness of 0,030 mm, resulting a total of 1566 layers (see § 6.3.1).

○ While, during the additive fabrication, additional issues risk occurring that determine irregular powder distribution, such as the recoater blade hitting certain rising areas already sintered, these events did not influence in a noticeable way the fabricated parts structure (see § 6.3.2).

○ The post-processing phase of the metallic SPD fabrication requires the building platform and parts extraction from the fabrication area, a stress relieving procedure, through a thermo-curing cycle and the parts removal from the building platform, usually performed with a wire EDM. Due to the material hardness, the boss threaded hole is recommended to be performed by EDM (see § 6.3.3).

○ The assembly can be easily integrated into the measuring set-up, but it can also suffer improvements to the holding area, improvements which are certain to appear with the extensive use of the SPD and increase of the number of laser interferometer models for which it is used (see § 7.1).

○ The ISO 230-2 standard was used. It describes the measuring procedure for CNC axes evaluation. (see § 7.1.1).

○ Validation of the new achieved splitter positioning device was performed by using a simple laser interferometry system and a laser interferometry system including the considered device for linear position, within consecutive tests and parallel tests, in laboratory and industrial conditions, with a continuous evaluation of environmental parameters (see § 7.2, 7.3 and 7.4).

The comparative measurements performed in this thesis have shown that SPD meets its requirements.

(5) To the achievement of the main objective of the research and development doctoral activity, the present PhD thesis brings several contributions, of which the most important are as follows.

• The profound analysis of the actual state of the art on measuring processes and systems, including interferometry and interferometers, additive manufacturing of grippers and mounting parts, lattice structures, as well as defining the main objective of the foremost research and development doctoral activity as structure and attributes development of laser interferometry systems.

• Development of defining analytical descriptors for general structure and characteristics of laser interferometry systems, referring to measurement object, coordinate system, lasers, laser beams, optics, output beams, detectors, environmental sensors and compensation modules, electronics, process software and computer(s), assembly, calibration, and other elements.

• Conceptualization, design and finite element simulation of a beam splitter new positioning device, based on creation and analysis of several different constructive variants, with optimization by integrating lattice structures to reduce its weight.

• Manufacturing of the splitter positioning device parts, by selective laser sintering of polyamide device variants, and by direct metal laser sintering of superalloy device variant, as well their preliminary evaluation.

• Validation of the new achieved splitter positioning device, by including it in a laser interferometry system structure for linear position, performing measurements within consecutive tests and parallel tests, in laboratory and industrial conditions, leading to development favourable results, but also regarding the generic calibration with laser interferometry systems.

* * *

The present PhD thesis, by problematic, approach and results, develops a series of studies, analysis, concepts, designs, parts and experimental results concerning the development of an innovative splitter positioning device to be included in laser interferometry systems.

The *scientific importance* of this thesis is sustained by its contributions to: development of defining analytical descriptors for general structure and characteristics of laser interferometry systems; conceptualization, design and finite element simulation of a beam splitter new positioning device, with optimization by integrating lattice structures; manufacturing of the splitter positioning device parts by direct metal laser sintering of a superalloy powder; validation of the new achieved splitter positioning device by performing measurements in laboratory and industrial conditions, leading to development favourable results.

The *practical importance* of this thesis consists in the fact that the achieved descriptors for general structure and characteristics of laser interferometry systems, part conceptualization, design, fabrication and validation on the beam splitter new positioning device are useful, by case, to individuals, students, academic staff, industry specialists, various educational and economic organizations, to increase the laser interferometry systems matters.

The problematics of laser interferometry systems, as potential perspective on interacting processes, analytical modelling and operational characteristics associated to laser interferometry systems, in order to develop their applications in active industrial environments, requires a complex, continuous and profound research and development activity.

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