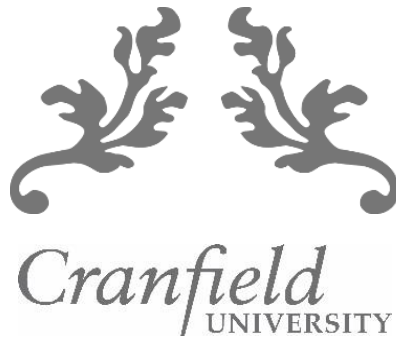




Claude SANZ

**ROTARY MOUNT DESIGN FOR
A CHROMATIC CONFOCAL SENSOR,
INVOLVING ADDITIVE MANUFACTURING
AND AN OPENED AIR BEARING**

School of Applied Science
Precision Engineering Institute

Ph.D. in the Metrology Department
Academic Year: 2014 - 2018

Supervised by Claudiu Giusca,
formerly by Paul Morantz with Paul Shore as associated supervisor
February 2018



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This thesis is submitted in partial fulfilment of the requirements for
the degree of Doctor of Philosophy

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ABSTRACT

In the field of high energy physics, the characterisation and positioning in space of a wire with a diameter of 0.1 mm is one of the steps to increase the precision of future accelerators' pre-alignment. This reference wire is measured within a high accuracy Coordinate Measuring Machine (CMM) to reduce its positioning uncertainty. No sensor could measure the wire position within the targeted uncertainty. This thesis addresses this issue by proposing a design for the Shape Evaluating Sensor: High Accuracy & Touchless (SESHAT).

The SESHAT operates a chromatic confocal sensor. The sensor is fixed to a rotor with a radial opening to allow the stretched wire to traverse it. This rotor is guided by a high precision air bearing controlled by a piezoelectric actuator. The mass limit for the stylus system of the CMM entailed the additive manufacturing of a hollow rotor. The high likelihood of particles on the wire surface involved a form deviation capability for the SESHAT, to reduce position measurement uncertainty.

The aim of the research was to design a sensor enabling the Leitz Infinity CMM to perform non-contact form measurement on the PACMAN reference wire to permit its axis positioning with an uncertainty such that $3\sigma < 0.5 \mu\text{m}$. The novelty emphasised in this thesis is focused on three main contributions. The form measurement uncertainty reduction obtained by using a chromatic confocal sensor for non-contact measurement on a wire surface is the first contribution. A mathematical model describing the behaviour of air pads over a through hole in the bearing surface composes the second contribution to knowledge. The demonstrated ability to obtain a micrometric form deviation on a rotary symmetric complex shape generated by additive manufacturing of titanium is the third contribution.

Keywords:

Metrology tool, High Precision Mechanics, Reference, Alignment, Particle Accelerator, Compact Linear Collider CLIC, Coordinate Measuring Machine, European Centre for Nuclear Research CERN

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test benches for the qualification of the air pads' behaviour over a hole in the bearing surface. Hélène Mainaud-Durand and the PACMAN team who led the PACMAN project, helped us with ideas, manuscripts redaction and plannings. Antonio Marin who helped me with the implementation of the tests aiming to determine the capacitive sensor's suitability and to evaluate the confocal chromatic sensor, dealing with the interface between hardware and software. Paul Morantz who helped me to set up my mind many times, who was available to understand my problems and lead me through them by giving me the right instructions to follow in order to solve them. François Morel who drew the computer-assisted drawings following my instructions, provided me with information like nominal distances between the parts and printed the technical drawings. The company Precitec, who performed the calibration of the sensor used in this work, including the evaluation of the systematic error due to an angle. Thomas Sahnner who focused with Claudiu Fichera, François Morel and Romain Gérard on the research and acquisition of a software to perform mass/performance optimisation before the additive manufacture of the SESHAT's stator. Thomas Schneider who performed the spectrometric measurements on the wire. Paul Shore who slipped relevant advice and names of authors or books when needed. All the ones who helped with my manuscripts revision and this thesis correction, including my manuscript reviewers and my thesis examiners. All CERN colleagues and companies representatives who took some time to answer my questions about their fields and to provide me with the different parts and tools needed for my work and the CERN organisation for the work environment and the safety they offered to me.

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LIST OF ABBREVIATIONS

AM	Additive Manufacture/d/ing
CAD	Computer-Aided Drawing
CERN	European Council for Nuclear Research
CFW	California Fine Wire company
CFRP	Carbon Fibre Reinforced Plastic
CLIC	Compact Linear Collider
CMM	Coordinate Measuring Machine
EDM	Electron Discharge Machining
ESRF	European Synchrotron Radiation Facility
FFT	Fast Fourier Transform
GF	Good Fellow company
laser	Light Amplification by Stimulated Emission of Radiations
LVDT	Linear Variable Differential Transformers
PACMAN	Particle Accelerator Components' Metrology and Alignment to the Nanometre scale
SLM	Selective Laser Melting

CHAPTER 1 INTRODUCTION

CERN, the European Organisation for Nuclear Research (originally named *Conseil Européen pour la Recherche Nucléaire*), is a worldwide leading high energy physics laboratory (www.cern.ch) that was created after the Second World War, promoting peace in Europe by bringing together researchers of different nationalities. Currently, CERN is the largest laboratory in the field and operates beams at high energy level, which have not been matched anywhere in the world. This allows the laboratory to enhance the global knowledge in the chosen field and provide citizens with a unique education and work environment. Students and researchers join CERN's community through different training programmes. The research presented in this thesis is part of a project funded under Marie Skłodowska-Curie Innovative Training Network by the European Commission. The project is called Particle Accelerator Component's Metrology and Alignment to the Nanometre scale (PACMAN).



Figure 1-1: Large Hadron Collider underground path and experiences

Current CERN facilities include the Large Hadron Collider (LHC), pictured in Figure 1-1, which accelerates protons and antiprotons reaching an energy of 14 TeV at the collision point. The knowledge developed in LHC also helps to develop new accelerating structures, such as the Future Circular Collider (FCC) or the Compact Linear Collider (CLIC). FCC and CLIC possible paths appear in Figure 1-2. The FCC would be a circular accelerator based on the same principles as the LHC, targeting the highest energy level ever reached of 100 TeV at the collision point. The CLIC would be a linear positron-electron collider aiming to an energy of 3 TeV. Electrons and positrons are elementary particles providing data with a reduced noise during particles interactions, compared to protons composed of quarks. The research work presented in this thesis is part of the CLIC study.

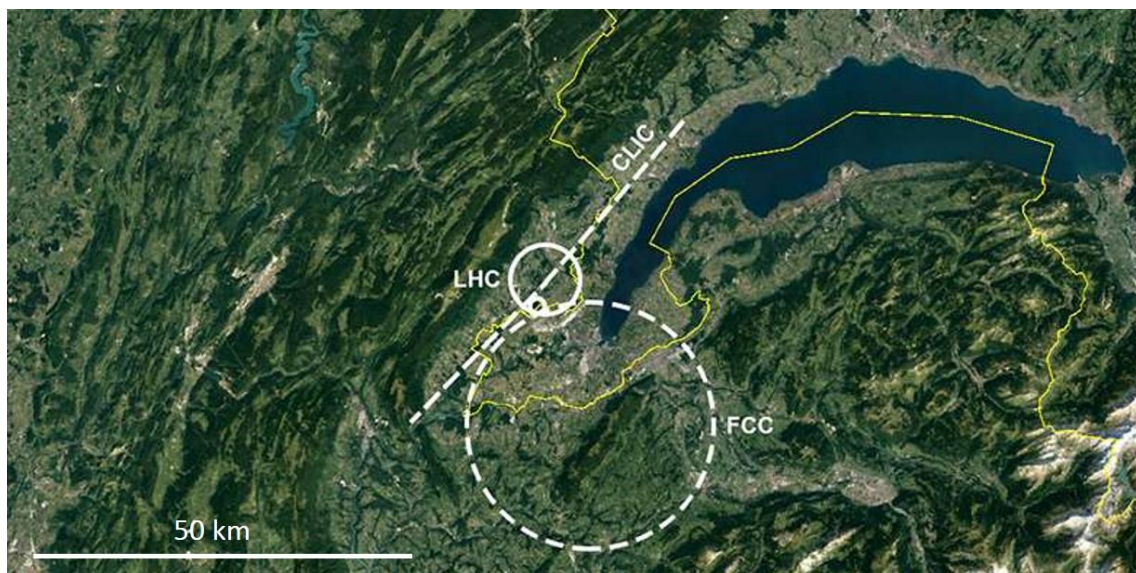


Figure 1-2: Possible underground paths of two future accelerator facilities at CERN: CLIC and FCC

One of the challenges of the CLIC is to keep a high luminosity along its length. High luminosity means high density of particles in the beams, which increases the chances of observing a phenomenon interesting for the physicists. The luminosity is optimised with accurate alignment between the tens of thousands of elements of the collider, partly represented in the artistic view of the accelerator presented in Figure 1-3. The tolerance zone of the functional axis of the components is summarised by a 200 m long cylinder with a radius of 14 μm that can slide along the full length of the collider, which appears in Figure 1-4 (the

cylinder) together with the functional axes of the components (the red dots). The alignment is achieved by simultaneously adjusting the positions of the elements, which relies on the measurement of the size, shape and relative position of the beam of particles inside each accelerating structure after a pre-alignment phase. This research work contributes to the pre-alignment feasibility study of the CLIC.



Figure 1-3: Artistic view of the underground Compact Linear Collider

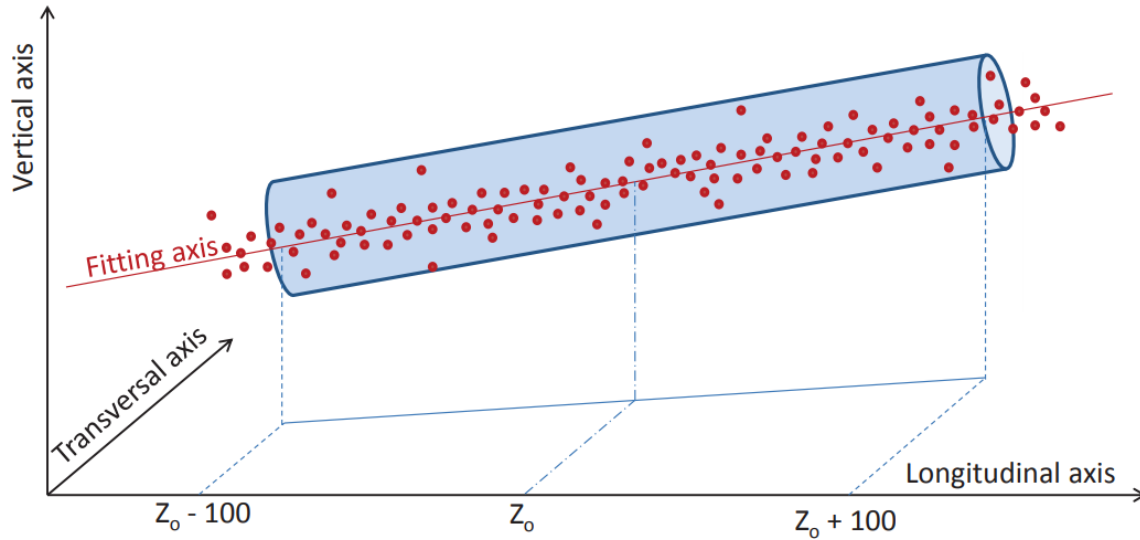


Figure 1-4: Illustration of the alignment tolerance (Aicheler et al., 2012)

The pre-alignment in the tunnel is based on the positioning of references (fiducials) attached to each element with respect to linear alignment references attached to the tunnel. A preliminary phase of the pre-alignment is to define the position of the functional axis of an element with respect to its fiducials, which is done in a metrology laboratory. This phase is called the fiducialisation process. Fiducialisation is required for all the elements later used in the tunnel: accelerating structures, magnets and beam position monitors. The quadrupole magnet, shown in Figure 1-5, focuses the beam of particles. If the CLIC is built, several thousands of quadrupole magnets, accelerating structures and beam position monitors will be fiducialised before being installed in the tunnel. In order to ease their transfer to the tunnel after their fiducialisation in a laboratory, some will be assembled together. The research work presented in this thesis serves the fiducialisation process of a quadrupole magnet and its pre-assembly.

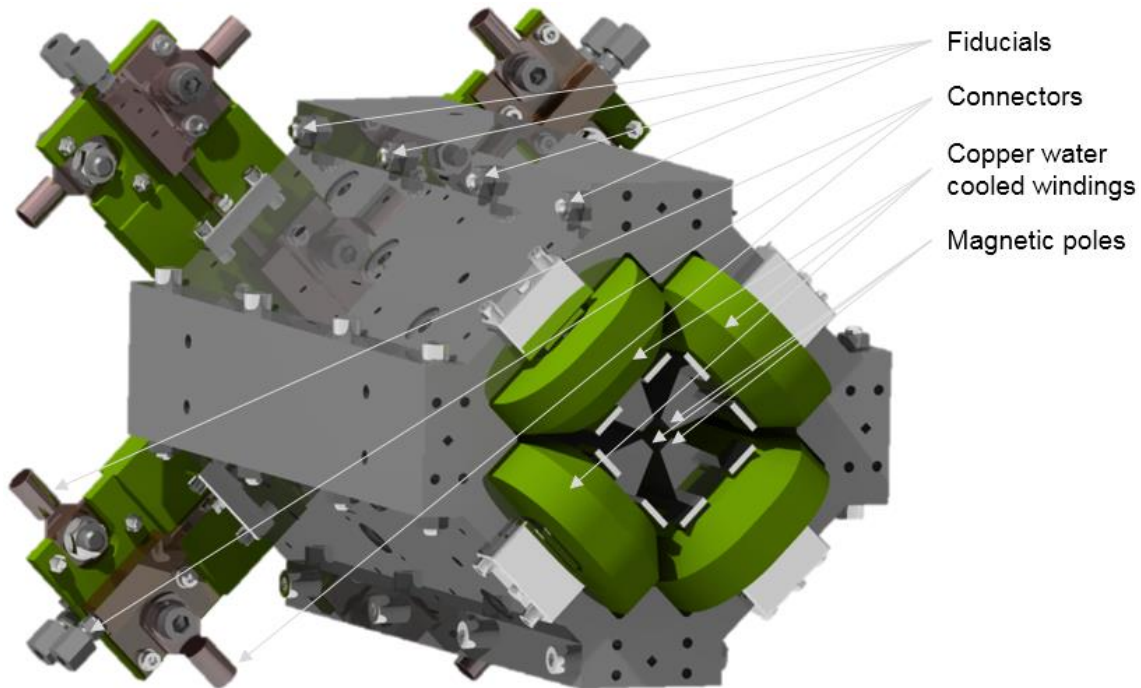


**Figure 1-5: Computer aided-drawing (CAD) of a quadrupole magnet
the copper windings appear in green at the forefront**

To make it easier to follow the advancements, the Particle Accelerator Component's Metrology and Alignment to the Nanometre scale (PACMAN) project was created. The aim of the PACMAN project is to improve the fiducialisation process by using a Coordinate Measuring Machine (CMM) with low measurement uncertainties (Friedsam et al., 1989) and by reducing the measurement time.

The PACMAN team is composed of ten PhD students from universities of member countries, who are supported by academic and industrial supervisors. Each student had a specific task to perform among length measurements, magnetic measurements, seismic vibration measurement, micrometric alignment, electrical characterisation, nano-positioning and high precision assembly. The research work presented in this thesis was done by one of the three students working in metrology.

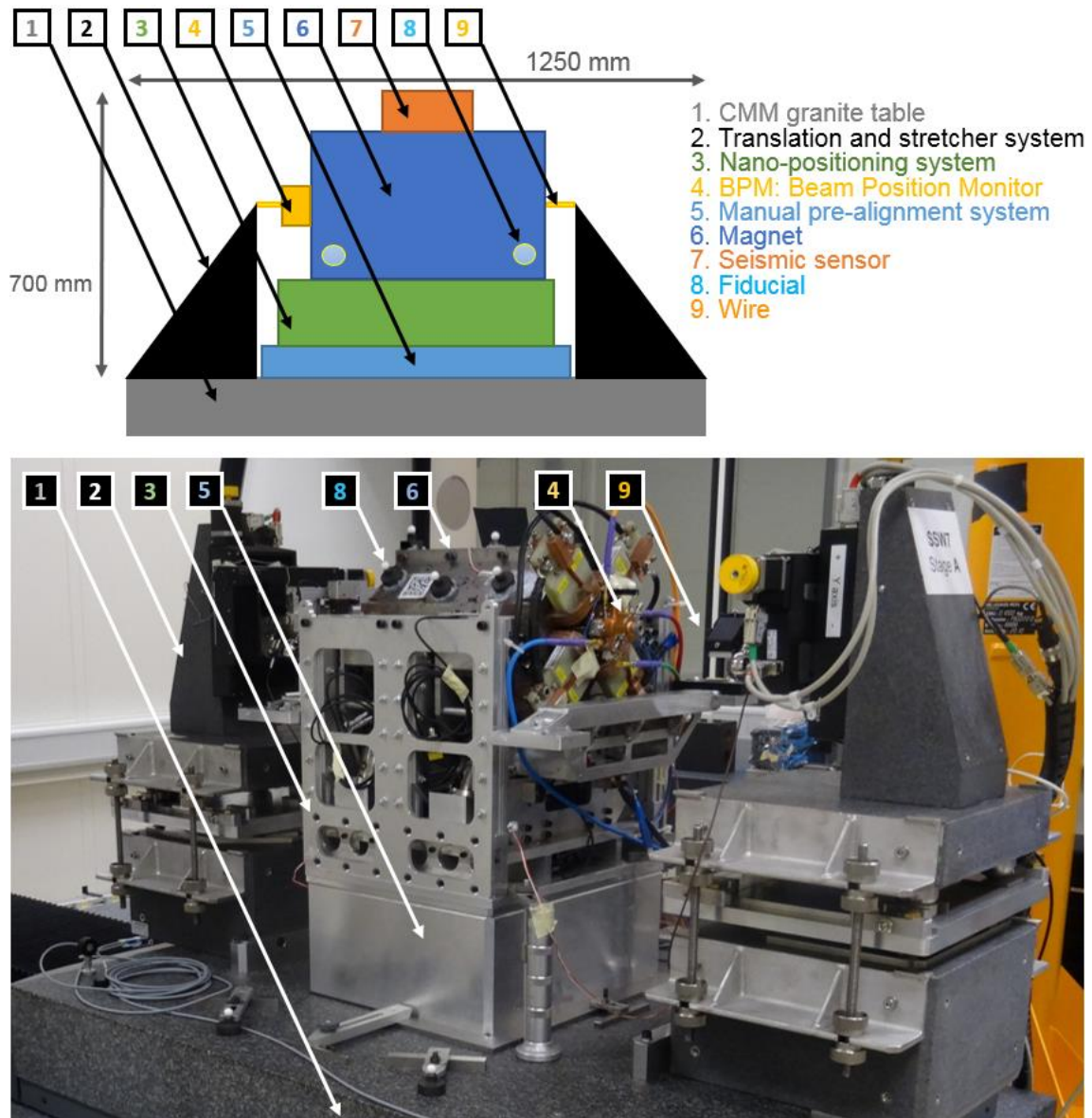


Figure 1-6: PACMAN test bench
 on which all the new technologies developed throughout
 the PACMAN project were installed and tested.

A team of researchers with different expertise constructed a pre-assembly prototype, shown in Figure 1-6, and mounted it on a CMM table. It is called the PACMAN test bench. The chosen CMM, a Leitz Infinity CMM, is a non-portable dimensional metrology tool that provides measurements in Cartesian coordinate systems (see Figure 1-7). The CMM's measuring volume of $1.2 \text{ m} \times 1 \text{ m} \times 0.7 \text{ m}$ and load capacity of 750 kg fits the requirements of the PACMAN bench.

The magnet fiducialisation aim is to express the position of the zero axis of the magnetic field (axis with which the particle beam should be aligned) in a

coordinate system based on the fiducials (number 8 in Figure 1-6) installed on the magnet's external parts. The CLIC error budget for this operation is $7\text{ }\mu\text{m}$. To do so, the first step is to determine the position of the magnetic zero axis. This is done using the stretched wire technique explained in details in the literature (Zachary Wolf, 2005). As the alternative current excites the wire at its resonance frequency the stretchers (number 2 in Figure 1-6) help to align the wire (number 9) within the magnetic field. The next step is to measure the wire position with respect to the fiducials (number 8 in Figure 1-6).

The motivation of the work presented in this thesis was to optimise the measurement of the wire using the Leitz Infinity CMM, which is depicted in Figure 1-7.



Figure 1-7: Leitz Infinity Coordinate Measuring Machine
the table moves along the X-axis, the vertical column ranges the Z-axis
while it scans the Y-axis carried by the horizontal bridge

To assure efficient electron acceleration, the uncertainty associated with the measurement of the relative position of the magnetic axis to the fiducials position should be at least an order of magnitude smaller than the alignment tolerance of the accelerating structures.

1.1 Measurement uncertainty

Measurement errors prevent metrologists to know the true value of a measurand (BIPM, 2008). Errors cannot be eliminated, nevertheless, they can be minimised (JCGM, 2008a). There are two types of errors:

- Systematic errors consist of a repeatable bias in the measurement results. They can be minimised by correction. However, the measurement uncertainty factors such as instrument resolution limits the systematic error correction process. For instance instrument correction is widely used in CMMs (Calvo et al., 2016; Schwenke et al., 2008; Weekers and Schellekens, 1997).
- Random errors consist of stochastic variations in the measurement results. Some random errors can be reduced to a minimum level by isolating the measurement instruments from the sources of these errors. For instance, a source of random error is the earth vibration due to some traffic near the laboratory. Either the traffic can be stopped, or the measurement system can be isolated from the ground to reduce the influence of the traffic on the results.

Measurement uncertainty is a “non-negative parameter characterising the dispersion of the quantity values being attributed to a measurand, based on the information used” (BIPM, 2008). The quantity values attributed to a measurand include random and systematic errors, which cause the dispersion. Errors can be modelled by probability distributions and thus uncertainty can be quantified by a variance or standard deviation.

Uncertainty analysis are separated into two types (JCGM, 2008a): statistical evaluation of random errors resulting from many measurements consist in Type A uncertainty analysis; any other evaluation method belongs to Type B uncertainty analysis. Combined standard uncertainty can be obtained from standard uncertainties using the law of propagation of uncertainties. This law

requires a model of the measurement which is given by a function f such that a measurand y is obtained from n input quantities x_n , following equation (1-A):

$$y = f(x_1; x_2; \dots; x_n). \quad (1-A)$$

The law of propagation of uncertainties is such that a combined standard uncertainty u_c for i sources can be obtained from the following equation (1-B) (JCGM, 2008a):

$$u_c^2(y) = \sum_{i=1}^N \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i) + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N \frac{\partial f}{\partial x_i} \frac{\partial f}{\partial x_j} \text{cov}(x_i, x_j). \quad (1-B)$$

If the sources i and j are uncorrelated, the second part of equation (1-B) is zero. The sensitivity coefficient $\partial f / \partial x_i$ provides information on the importance of the contribution of source i to the combined standard uncertainty. If the function f is nonlinear and a first-order Taylor expansion of the uncertainty is not a relevant approximation of f , or if a normal distribution model is not a relevant approximation for the probability of the output, among other limitations, then other approaches are required to combine standard uncertainties. The Monte-Carlo propagation method is one of them, presented in GUM supplement 1 (JCGM, 2008b). This propagation method is based on a measurement model simulating measurement results. Numerous inputs with parameters randomly generated from their associated uncertainty distributions are propagated through the model. The measurand and its simulated errors compose the output, leading to the associated standard uncertainty after a statistical analysis. Monte-Carlo is often applied to the uncertainty propagation through coordinate measuring machines (Balsamo et al., 1999).

Calibrated length measurement systems provide traceable measurement results. Such results can be related to stated references through an unbroken chain of comparisons all having measurement uncertainties. The universal definition of the metre is one of the stated references: "The metre is the length of the path travelled by light in vacuum during a time interval of $1/299\,792\,458$ of a second" (NIST, 2008). For example, traceable measurement results can be achieved after calibration of the measurement system using a calibrated artefact (or gauge), which is a physical object reproducing a measurable quantity. The length of a

gauge is traceable if it has been measured by a calibrated chain of measurement systems, comprising, for example, an interferometer (Byman et al., 2018). A measurement system can be calibrated using a gauge with a certificate of traceable measurement result prior to a measurement. The user of the measurement system can then evaluate the traceability of its measurement results, which agree with the national standards within the resulting uncertainty provided that proper care was given to the uncertainty evaluation. Additionally, traceable measurement results are comparable worldwide with other traceable measurement results.

The uncertainty in fiducialisation processes results from the combined uncertainties brought by the coordinate measuring machine errors, the part to be measured, the environment, the sensor system and the operator.

1.2 Measurement requirements and research hypothesis

The fiducialisation process requires high precision measurements performed on distinct parts of a metre-large assembly. The specific measurement conditions during the fiducialisation are:

- There is a magnetic field around the quadrupole magnet.
- There are many elements in a limited space, which restricts the access of the measurement system.
- The measurement is done with the CMM working conditions.
 - The temperature is controlled and no heat source should be brought in the room.
 - The maximum mass for a probe is limited.
- A single wire is used for the measurements performed on the different components of the CLIC.
- Once the wire is positioned in place, it becomes a reference and nothing should alter its position

These measurement conditions led to four main questions:

- Is the wire the best reference for all the different measurements performed with it (4.3)?

- Are there existing sensors able to acquire the position of a wire on the Leitz Infinity and how good are they?
- Is the Leitz Infinity CMM affected by a magnetic field?
- Is the Leitz Infinity CMM capable to measure accurately the wire position using a non-contact probe?

The answers to these questions were partially found after a brief literature review, see chapter 2, and some tests, see paragraph 4.2, and can be concluded as follows:

- The copper-beryllium wire with a diameter of 0.1 mm is a good reference for the project but its form error is a large source of uncertainty
- The wire must be measured with non-contact techniques.
- No sensors available on the market are able to measure the form error of the wire with an accuracy relevant for the PACMAN project.
- A chromatic confocal sensor is a good candidate for form measurement if used in optimal conditions: with its axis as perpendicular as possible to the measured surface (A.4.3). This led to the concept of the SESHAT (1.3).
- In the conditions required for the wire position measurement, a magnetic field does not significantly contribute to the Leitz Infinity CCM errors.
- The Leitz Infinity CMM has a measurement volume compatible with the requirements of the project and a low MPE_E (see 2.1)
- The versatile LSP-S4 probe, which allows for integrating external measurement systems that replaces the stylus system, is compatible with the integration of a new wire measurement system.

These considerations led to the development of the core research presented in this thesis, which is based on the following hypothesis:

An optical form measurement sensor can be adapted to a high-end CMM to improve the stretched-wire-based fiducialisation process of CLIC components.

1.3 Shape Evaluating Sensor: High Accuracy & Touchless (SESHAT)

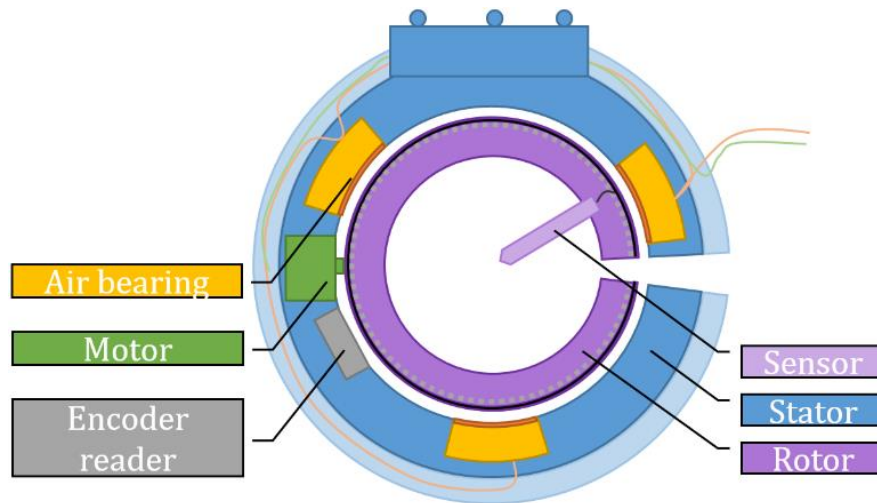


Figure 1-8: Schematic of the SESHAT design concept

The SESHAT is an optical probe system that allows the measurement of the PACMAN wire form and position with the Leitz Infinity CMM. It is based on a rotary mount designed to reduce the angle between the optical axis of the sensor and the surface normal of the sample to be measured.

The SESHAT is composed of the different elements introduced in Figure 1-8 and Figure 1-9. An air bearing is leading a rotor supporting the chromatic confocal sensor. The rotor is controlled by an actuator. Before the rotor reaches a critical point due to its opening, some end-stops limit its progression. The position of the rotor is given by an encoder composed of a read-head and a scale. The stator holds the elements (air pads, actuator, encoder reader...) and has a plate featuring three balls and a hole for a hook to ensure mounting on the LSP-S4 probe.

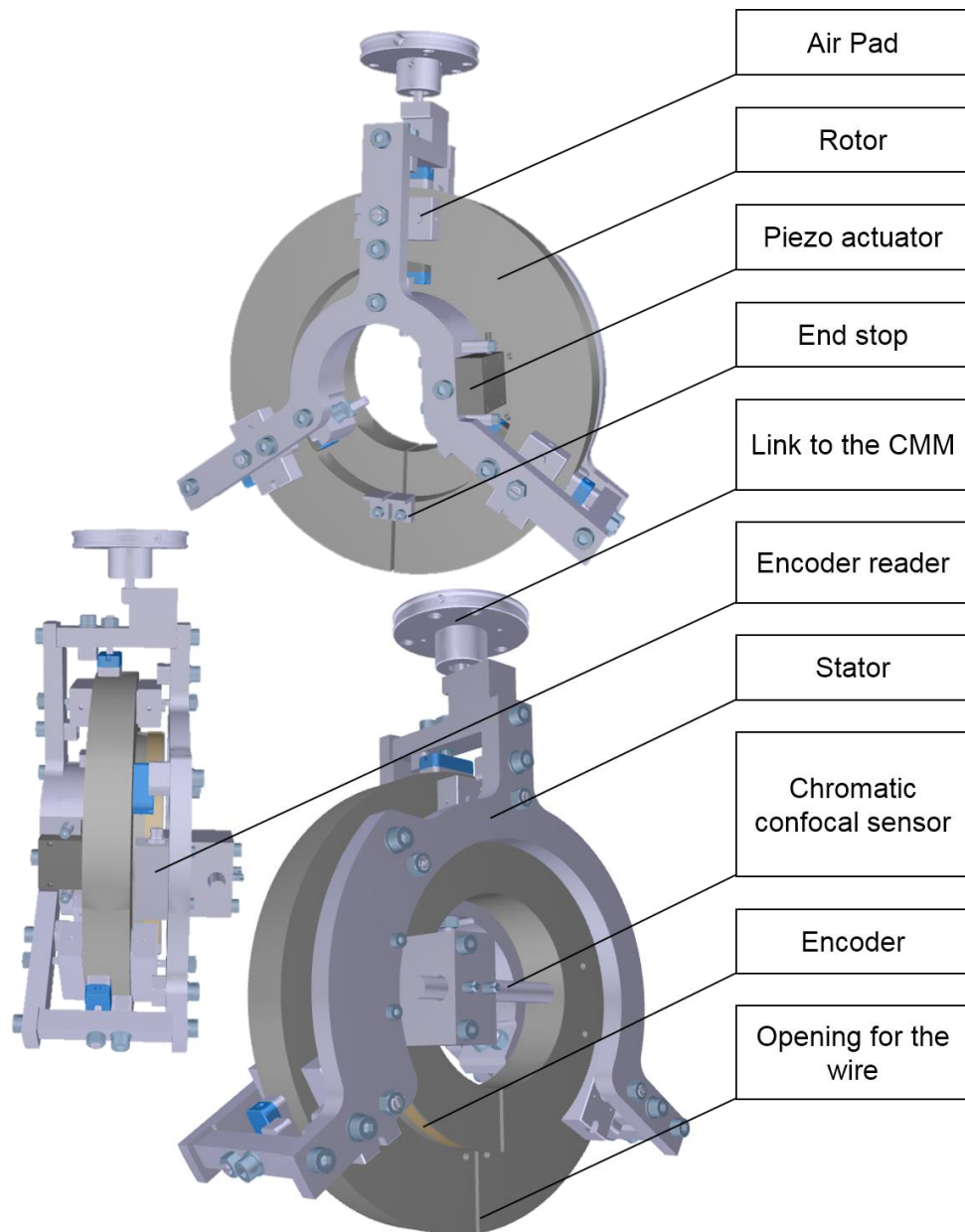


Figure 1-9: Introduction to the SESHAT's main elements using three views of an intermediate state of the design

The novelty of the design consists in an opening of the rotor in the radial direction allowing the stretched wire to go through the bearing and to be positioned in front of the sensor, along with the axial direction. The SESHAT should fit with the requirements implied by the PACMAN project:

- 1) Perform non-contact measurements with 0.5 μm repeatability
- 2) Be as light as possible (maximum mass of 1.2 kg)

- 3) Made of non-ferromagnetic materials and components which are not affected by magnetic fields reaching up to 20 mT
- 4) Not creating any magnetic field larger than 0.1 mT
- 5) With the highest possible stiffness (minimum of 100 N/ μ m for the rotor)
- 6) Emitting as little heat as possible and with a repeatable thermal behaviour

The letters of the acronym SESHAT compose the name of the Ancient Egyptian goddess of writing, accounting and measurements, Seshat (Mark, 2016), depicted in Figure 1-10.

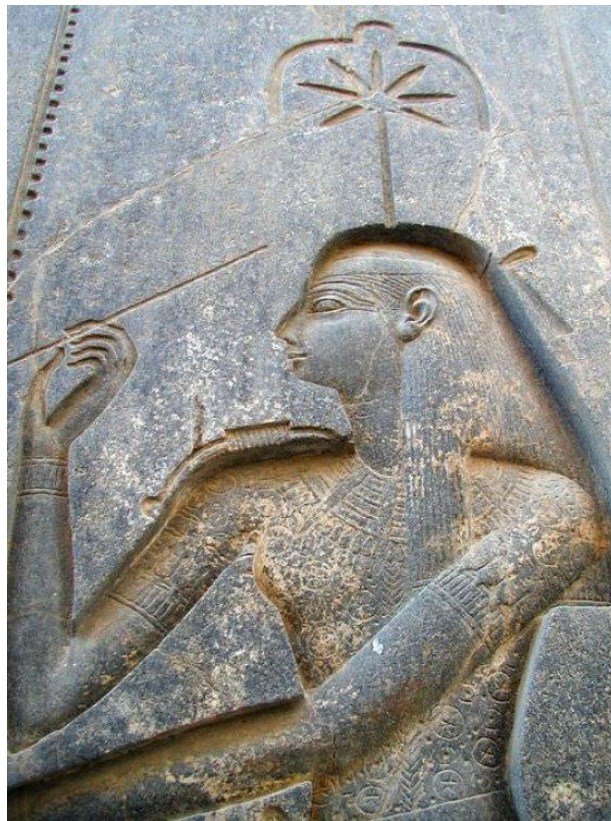


Figure 1-10: Seshat, goddess of writing, accounting and measurements engraved in the Luxor Temple (Mark, 2016).

1.4 Thesis structure

Chapter 1 introduces the need for the research, its environment and its context.

Chapter 2 contains a literature survey introducing the scientific background of metrology, showing gaps in technology.

Chapter 3 introduces the research approach, the objectives and methodology.

Chapter 4 provides the validation of the choice of the reference for the project, followed by the proof of feasibility of wire roundness measurement. The results of the wire roundness measurements show that the wire roundness is the main concern for measurement uncertainty and that a position measurement including roundness evaluation is required to reach the main target.

Chapter 5 presents the SESHAT: the proposed measurement system able to perform roundness measurement and wire position measurement. The motivations leading to the choice for the different components of this sensor are given.

Chapter 6 discusses the research work performed to determine whether a cylindrical high precision bearing can work with an opening in the rotor. The air pads used for the SESHAT are introduced and a model predicting their behaviour over a slot is presented. The validation tests and the results are introduced.

Chapter 7 discusses the possibility of having a light air bearing. The proposed solution is a titanium rotor built using additive manufacturing and machined at best. The results are presented and discussed.

Chapter 8 is the closing chapter, which comprises the summary, future work, discussion and conclusion.

CHAPTER 2 LITERATURE REVIEW

This section presents a brief literature review of the current state of art of the measurement technology that can be used in fiducialisation process. This review was used to find the gaps in technology (2.6) that led to the development of the SESHAT.

2.1 Coordinate measuring machines

A coordinate measuring machine (CMM) is a device able to support and move a probing system capable of recording the position of points belonging to actual surfaces of a measured part in a spatial coordinate system. The machine consists of:

- a mechanical frame (see Figure 2-1) composed of the coordinates axes with encoders that can be rotational or linear,
- a probing system (see Figure 2-2) composed of a probe-head (or probe) with a sensing element, that can be as simple as a switch or as complex as a compound multi-directional deformable assembly (see Figure 4-2), and a stylus system,
- a control unit that controls the CMM and communicates with a computer,
- a computer with software sending commands to the control unit and collecting and analysing the data points in order to extract the measurement results.

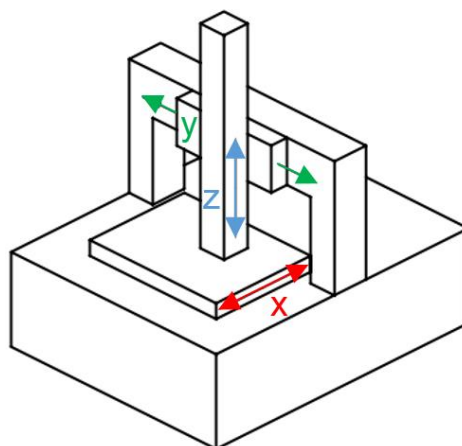
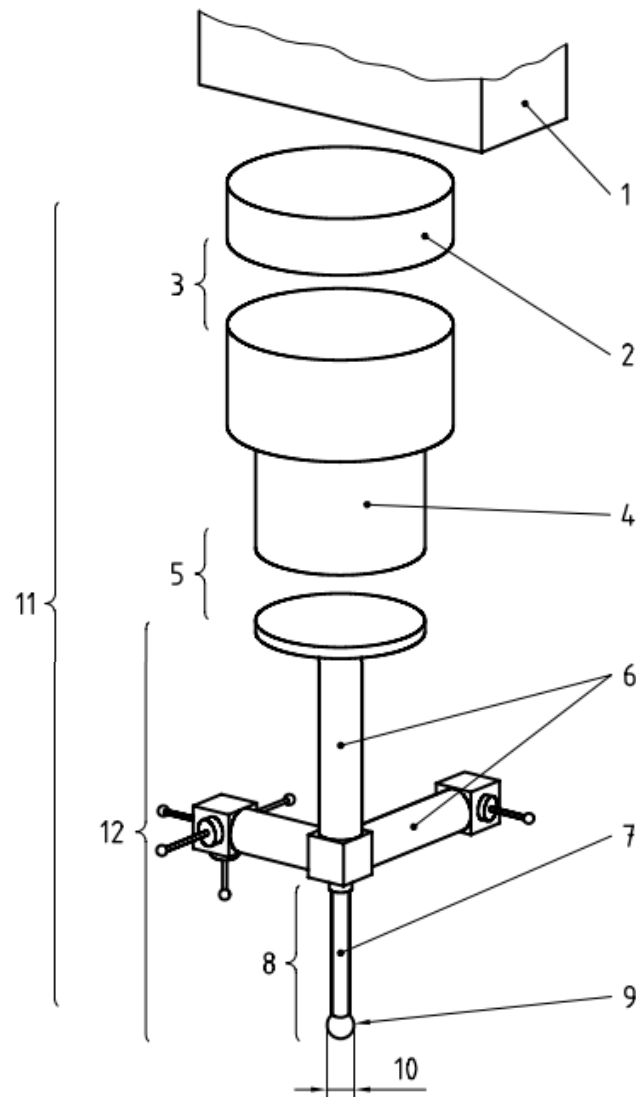


Figure 2-1: Fixed bridge CMM (ISO, 2001a), a schematic diagram and an example of the mechanical frame.



Key

1	Ram	7	Stylus shaft
2	Probe extension	8	Stylus
3	Probe changing system	9	Stylus tip
4	Probe	10	Tip diameter
5	Stylus changing system	11	Probing system
6	Stylus extension	12	Stylus system (composed of stylus system components)

Figure 2-2: Probing system (ISO, 2001a).

The CMM measurement uncertainty is affected by various influence factors:

- CMM design - The rules of precision mechanics play an important role in the design of a CMM (Hale, 1999), for example, the reduction of Abbe errors and isolation of the metrology frame from the sources of vibration. The stiffness

and coefficient of thermal extension of the frame, the pitch of the encoders' scales, the damping and the bearing systems have a high impact to the CMM's errors. However, the effect of some mechanical errors in CMM measurements can be evaluated and compensated for (Calvo et al., 2016; Schwenke et al., 2008; Weekers and Schellekens, 1997). The combined errors from all these sources are smaller than a "maximum permissible error of indication for size measurement" (MPE_E) for a given measured distance. This number is provided by the manufacturers, following the European standard (ISO, 2001a). For instance, the Leitz Infinity used in the PACMAN project has a $MPE_E = 0.3 \mu m + L/1000 \mu m$ for two probed points separated by a distance L , where L is expressed in millimetres (Hexagon, 2015), which would be represented by a curve similar to the curve appearing in Figure 2-3.

- Environment – When high accuracy measurements are targeted, the environment is controlled (temperature, humidity, vibrations). A vibrations (isolated floor), temperature (0.1 K/m, 0.2 K/hour, 0.4 K/day) and humidity controlled (40 % RH) clean room is used at CERN.
- Procedure – the procedure has a high impact on the results:
 - optimisation of the calibration;
 - selection of the optimised measurement system (Gaska et al., 2017);
 - best parametrisation of the measurement (Saunders et al., 2014), for instance choosing the correct number of measured points (Phillips et al., 1998) or the appropriate angle of approach.
- Operator – the operator can influence the results:
 - preparing the measured part (temperature, cleanliness, position on the machine, alignment...);
 - analysing the data.
- Measured part - The surface roughness and colour or presence of dust can influence the optical probes output. Elasticity of the measured part can influence the output of the contact probes. Chapter 4 will describe in detail the wire used to align the accelerator components (summarised in 4.3).

- Sensor system – measurement requirements lead to particular needs for CMMs or sensors; The influence of a magnetic field is an example that will be discussed in detail in the following section 2.2.

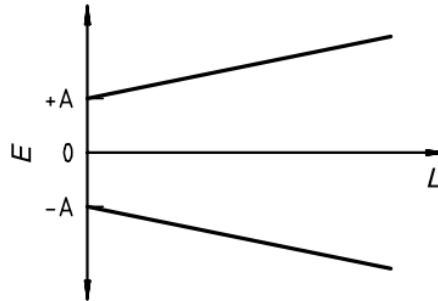


Figure 2-3: CMM maximum permissible error of indication for size measurement error MPE_E (ISO, 2001a)

2.2 Influence of a magnetic environment

The main-beam-quadrupole magnets emit a magnetic field during their fiducialisation process that may affect some parts of a CMM. Taking Renishaw probing systems for example, their technical specifications state that some probes are not suitable for operating in magnetic environments (Renishaw, n.d.). Nonetheless, some CMMs can cope with magnetic fields and even measure magnetic fields intensity within their measurement volume. For example, some Hall probes, depicted in Figure 2-4, were adapted for CMM use (SENIS, 2015). The behaviour of the Leitz Infinity CMM has not been evaluated in a magnetic environment despite this CMM is equipped with a probe-head composed of Linear Variable Differential Transformers (LVDT).

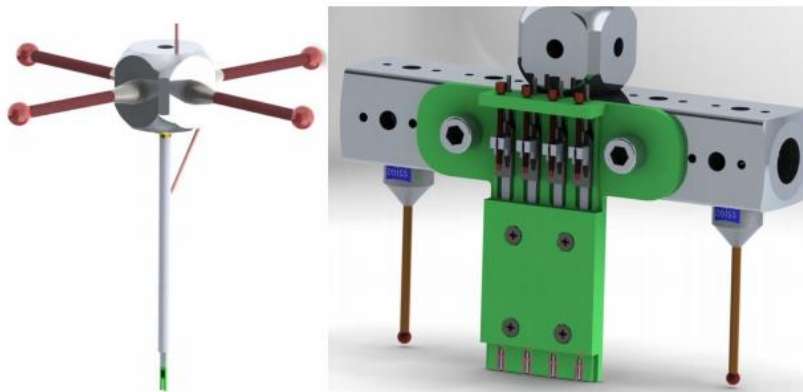


Figure 2-4: 3-axis single-probe (MMS-1i-CMM) and 3-axis four-probe array (MMS-4i-CMM) mounted on a standard CMM holder together with touch probes (SENIS, 2018)

An LVDT is a displacement sensor very resistant to tough environments and widely used (Ara, 1972). This sensor is composed of a primary exciting coil, two secondary reading coils and a ferromagnetic part sliding within the tube supporting the coils as depicted in Figure 2-5. This sliding part is attached to the element for which the position is to be determined, for instance the deformable plates in the LSP-S4 probe. The primary coil is exciting the system while changes in the slider's position are observable on the output from the secondary coil. These sensors are sensitive to temperature changes (Ara, 1972). These sensor's accuracy and resolution are normally limited by the acquisition system and the signal noise, nevertheless, they are influenced by magnetic fields.

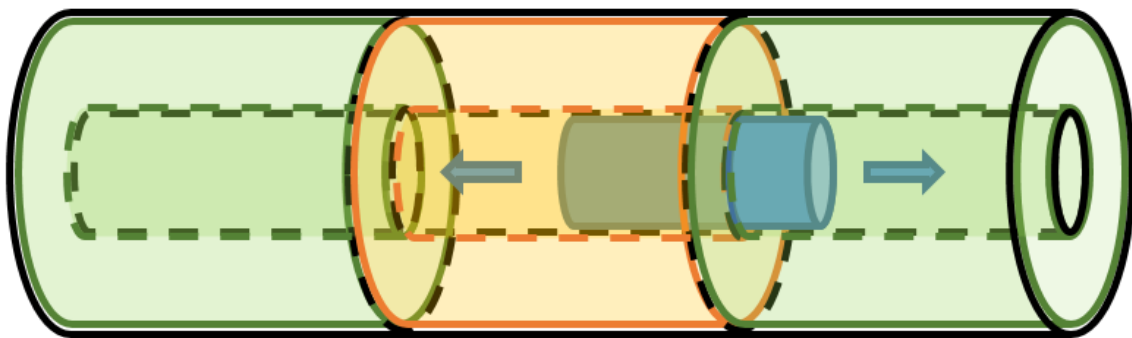


Figure 2-5: Illustration of the LVDT sensor
In black a foil separates the blue moving core from the orange primary winding and the green secondary windings

Martino et al. (Martino et al., 2010) observed the dramatic effect of a magnetic longitudinal fringe field on LVDTs. Such a field, showing a maximum of 1 mT with an insignificant transversal field, engendered measurement errors about ten times larger than the same errors in nominal conditions. The solution they modelled to reduce the errors was a magnetic shield applied together with a polarized direct current. Their model showed a measurement error reduction from 7 % to about 0.1 % of the measuring range.

Another model-based solution was proposed by Masi et al (Masi et al., 2011). Their research objective was to provide a mathematical tool predicting the response of LVDTs in magnetic fields where no calibration was possible. Models of LVDTs undergoing a magnetic field were created and validated by real measurements, with an accordance better than 80 % between their predictions and validation. Additionally, Spiezia et al. (Spiezia et al., 2011) studied the impact

of magnetic fields on two commercialised LVDTs. They showed that the nature of the supply (voltage or current) and the arrangement of the reading circuitry influenced the measurement uncertainty. Consequently, bespoke tests were performed in order to assess the behaviour of the Leitz Infinity CMM within a magnetic field, as reported in section 4.1.

2.3 Filtration

This section introduces the types of filters (ISO, 2006a) which were relevant in this research work.

The nature of a measurement requires to limit the spatial wavelength bandwidth of the acquisition. The role of a linear profile filter is to separate a profile into several components of similar spatial frequencies (ISO, 2006b). The spatial frequencies selected by a linear profile filter result from the choice of the cut-off wavelength of the filter. Half of the amplitude of a sinusoidal profile is transmitted by a filter when its wavelength is the cut-off wavelength of the filter (ISO, 2006b). Suitable cut-off wavelengths are provided in the norm on roundness measurement (ISO, 2011a) as a number of undulations per revolution (UPR). The roundness measurement of a cylinder with a diameter of 5 mm requires a filter transmitting from 1 UPR to 50 UPR. An example of linear profile filter defined by its cut-off wavelength λ_c , used in this research work, is the Gaussian filter (ISO, 1996a). The equation (2-A) of the Gaussian filter $s(x)$, with its Gaussian parameter $\alpha = \sqrt{\ln(2)/\pi}$ is the following:

$$s(x) = \frac{1}{\alpha \cdot \lambda_c} e^{-\pi \left(\frac{x}{\alpha \lambda_c} \right)^2} \quad (2-A)$$

Morphological filters can be used to reproduce the effect of a probe tip on a measurement set, for all shapes of probe tips and all measurement profiles (Lou et al., 2014). Additionally, according to the standard, morphological filters are filters which preserve the order of the inputs and whose outputs are constant if they are applied more than once on the same input (ISO, 2006c). In this document, morphological filters are applied to compare optical measurements and contact measurements (4.5.2.1).

2.4 Wire reference

Griffet (Griffet, 2010) performed a comprehensive literature review of fiducialisation methods and pre-alignment of components on a common support for the CLIC study. This review was extended with the study on more recent papers (Arpaia et al., 2014; Duquenne et al., 2014; Kashiwagi et al., 2012; Le Bec et al., 2012; Temnykh et al., 2010), however, a detailed analysis of the wire requirements is often missing.

Wolf (Zachary Wolf, 2005) introduces and solves the equations of motion of the stretched wire applied to magnetic measurements, discusses the different sources of errors that affect magnetic axis position measurement and provides typical values for the wire (wire diameter: 101.6 μm ; Mass per unit length: 67.7 mg/m; Resistivity: 76.8 n Ωm). These values are resulting from his choice of wire. He states the requirements on the wire characteristics, as listed below:

- non-magnetic to avoid disturbances of the magnetic field gradient in the quadrupole;
- high tensile strength to minimise the sag;
- small diameter to neglect the wire stiffness, but large enough so it is possible to use it.

Wolf used a 100 μm diameter copper-beryllium wire (Zachary Wolf, 2005). Typical values for wire characteristics given by their wire provider are written in Wolf's paper, they are in good agreement with the ones given by the providers of the similar wires used at CERN. The value of 100 μm was thus preferred for the PACMAN wire diameter.

Le Bec et al (Le Bec et al., 2012) considered two types of wires: copper-beryllium wires and titanium wires. The titanium was preferred as it was theoretically more suited for the application.

A comparison between three different wires was reported in 2014 by researchers from CERN (Duquenne et al., 2014): two copper-beryllium wires from different

years and a copper-niobium wire. The conclusion of the comparison was that the type of wire had no noticeable impact on the measurements results for quadrupole magnet fiducialisation. The fiducialisation was performed with non-contact capacitive sensors giving the position of the reference wire with respect to reference spheres. Later, the spheres were measured with a contact CMM, thus increasing measurement uncertainty by adding one step compared to the PACMAN aim. As Duquenne et al. averaged the wire surface position along its length using few centimetre long capacitive sensors, there was no need to estimate the surface texture of the wire.

The PACMAN project aims to measure the relative position of the external fiducials to the wire in non-contact mode. Therefore, the wire surface requires to be characterised, which will be discussed in 4.3.

2.5 Sensors

The sensor is the component that interacts directly with the surface of the part being measured during probing. The probe of the CMM used in PACMAN is equipped with a sensor that has flexible parallelograms whose position is measured by LVDTs, allowing low uncertainty on contacting measurements. The flexure of the parallelograms is recorded during its increase until the probing force is reached, and then the stylus tip is withdrawn from the surface of the part. This measurement system can be clamped, then the parallelograms are rigid and non-contact sensors can be carried by the probe-head on the same standard mount as contacting probe-tips.

The PACMAN setup requires the sensor to be:

- able to cope with medium to strong magnetic fields (up to 300 mT),
- able to measure the position of the axis of a copper-beryllium wire of a 100 μm in diameter, with a sub-micrometre accuracy,
- with a width not exceeding 100 mm,
- mass < 1.2 kg (including CMM's standard mounting plate mass).

The high-end sensor market includes a variety of non-contacting sensors. Among these, capacitive sensors have been demonstrated to work in radioactive

environment, with micrometre uncertainty (Mainaud Durand et al., 2014). Optical sensors based on the confocal principle are capable of sub-micrometre repeatability, as reported in Table 2-1. Some optical shadow-based sensors are designed for wire measurement. Some fringes recognition optical sensors (2.5.5) were developed to measure small features with high accuracy (LMI3D, n.d.). The principles of these sensors will be presented and their suitability for the project will be summarised in a Table 4-2 with the conclusion (2.5.6).

2.5.1 Capacitive sensors

A capacitive sensor consists of plates connected either to a voltage or to the ground (see Figure 2-6). The electrode and an external conductive target form a capacitor. After its linearization, the change in capacitance of this system provides the distance between the sensor reference point and the part being measured. The capacitance results from the geometry of the electrode, from the charge on the electrode and from the potential of the target. The limitations of this type of sensor are the guarding system's quality, the analysis system's quality and the mechanical stability of the sensor. Nevertheless, a distance of 100 μm could be evaluated with 100 pm uncertainty (Heerens, 1986).

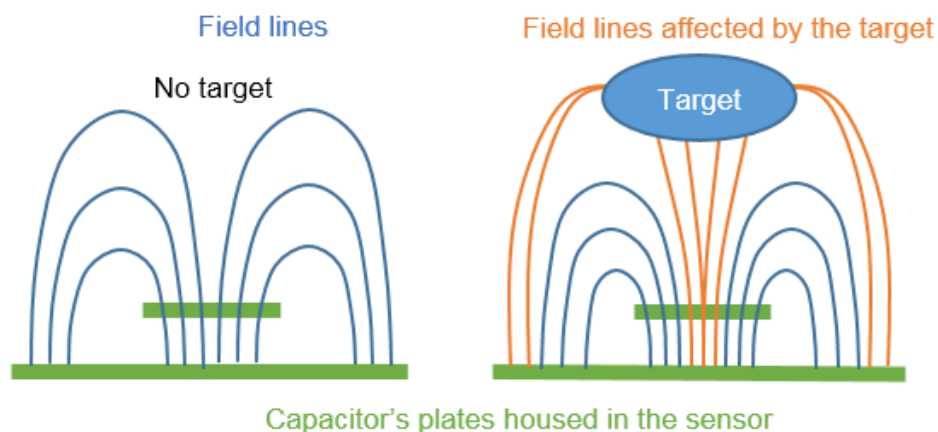


Figure 2-6: Illustration of the principle of the capacitive sensor
The capacitance is increased in the presence of a target.

2.5.2 Optical confocal sensor

The confocal principle is pictured in Figure 2-7: the only point detected by a confocal system stands at its focal point. A point light source S emits towards a micro-objective which focuses the light in a focal point F'. When the light

encounters an object's surface, this scattering surface reflects the beam. Consequently, a secondary point light source P appears on the object. If this secondary light source is in the focal point F' of the optical system, as shown in Figure 2-7 in orange with blue arrows, its light will come back through the optical system towards the light source S . On its path stands a beam splitter which lets the light coming from the source S traverse it while it reflects the light coming from the object point P . In the focal plane F of the return path stands a pinhole which filters out the light out of focus. Behind the pinhole, there is a sensor. In this configuration, if the light coming from the object is out of focus, namely focusing before or after the focal plane F , or aside the focal point (as shown in blue dashes in Figure 2-7), it is partially or totally filtered out by the pinhole. As a consequence, while moving along the optical axis, the intensity acquired by the sensor will go through a maximum which will indicate that the object is in focus, giving its position with high accuracy as the focal point position is well known (Tiziani and Uhde, 1994).

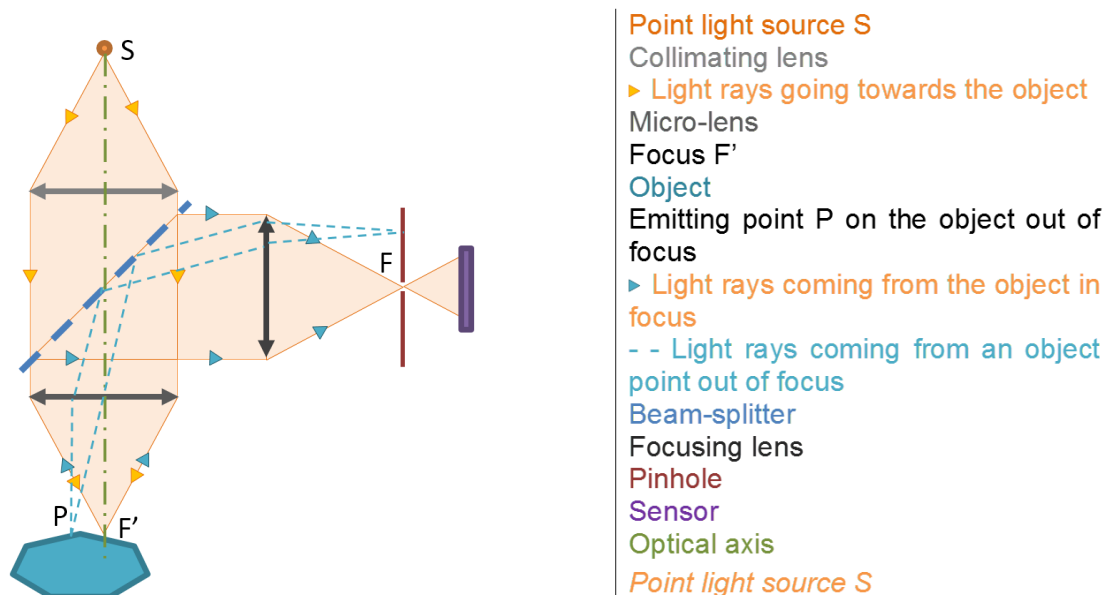


Figure 2-7: Working principle of a confocal system.

In order to obtain areal measurements, the micro-lens can be replaced by an array of micro-lenses (Tiziani et al., 1996) or by a larger lens and the pin hole by a spinning disk with a hole (Tiziani and Uhde, 1994) and the sensor by an array of sensors. The advantages of the confocal technique are its resolution along the optical axis (the repeatability can reach $0.1 \mu\text{m}$, see Table 4-2) and its ability to

filter physically the information from the object out of focus. Tiziani and his co-authors highlight that the confocal technique is sensitive to residual aberrations of the optics (particularly spherical aberration which spreads the focal point).

2.5.3 Optical chromatic confocal sensor

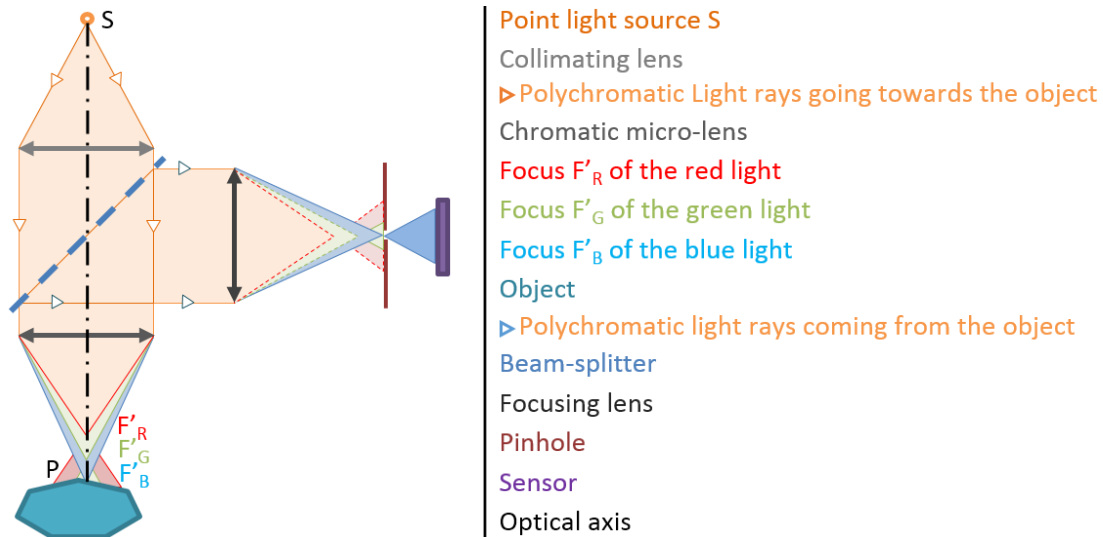


Figure 2-8: Working principle of a chromatic confocal sensor

The chromatic confocal principle is depicted in Figure 2-8. The axial mechanical displacement of confocal systems is replaced by an axial chromaticity in chromatic confocal systems. A polychromatic light source is focused by a highly axially chromatic micro-lens objective such that the light beam in focus on the object surface is close to being monochromatic. The intensity of the focused colour is the highest on the sensing elements. Because the axial chromaticity is well-defined, the colour of the light collected on the sensor contains information on the distance between a reference point of the sensor axis and the measured point on the sample (Tiziani et al., 1996). After an expansion of the beam by a matrix of chromatic micro-lenses, the illuminated areas of the object appear bright in a range of colours indicating the height of the different points, allowing for areal measurements. The colours can be determined either by spectral analysis or by a combination of the intensity data selected by several pass-band filters.

2.5.4 Optical shadow-based sensors

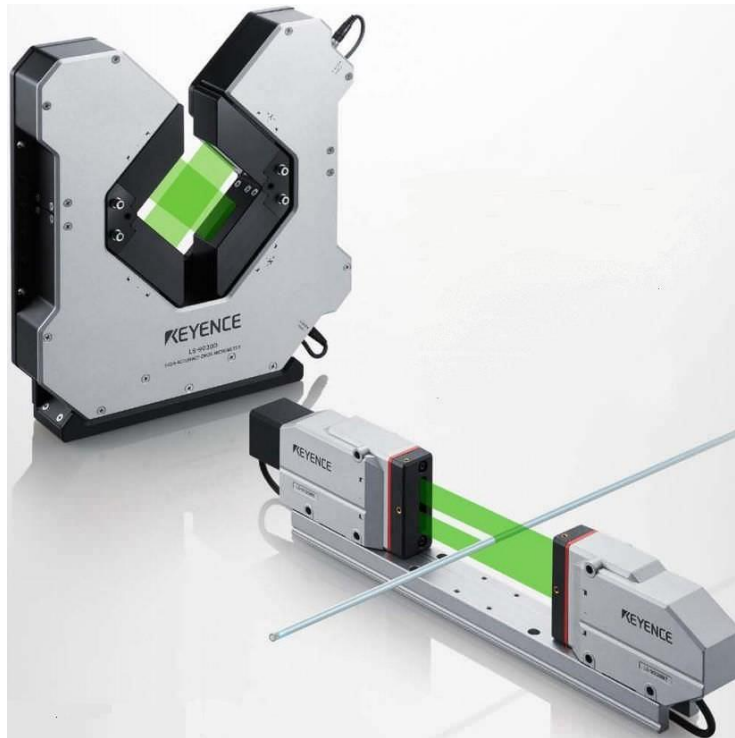


Figure 2-9: Shadow-based low uncertainty micrometres (courtesy of KEYENCE)

In shadow-based sensors, the part to be measured is placed between a source of light and a light-sensitive sensor, as shown in Figure 2-9. They are based on two different techniques: sensors based on edge detection of the shadow, and sensors based on a decrease in the intensity perceived by the receptor from which its position can be deduced. The repeatability of the corresponding sensors results from the technique applied to find the edges of the shadow. This principle has been previously used for fiducialisation (Wolf et al., 1999). The best mathematical strategy for edge detection has been studied since the early 70s: one of the universal sources of error in edge detection is the irregularity of the surface structure of the measured part (Davis, 1974).

2.5.5 Optical fringe-recognition sensor

The fringes-recognition technology relies on the analysis of the deformation of a singular optical pattern projected on a part. An optical system illuminates a surface using this pattern, which is simultaneously observed by a camera. An

algorithm analyses the acquired image and determines the phase of the light reflected by the measured part. Other algorithms convert the phases into distances. The distances can be converted into 3D coordinates after a linearization process. Gorthi and Rastogi state that the limits of this technique are due to the wavefronts in the observed fringe pattern. The errors result from the non-linearities of both the projection system and the camera (Gorthi and Rastogi, 2010).

2.5.6 Summary of the results and conclusion on the sensor choice

Other technologies, including, but not limited to, tomography, micro-tomography and ultrasonic waves, were considered but not reported in this review because they were obviously not relevant to the PACMAN wire measurement, given their excessive mass, size or measurement uncertainty. In Table 2-1, data either provided by the manufacturer or evaluated on the wire with the different sensors are reported.

Name of the sensor	Measurement Principle	Volume /mm ³ length×width×height	Mass /Kg	Repeatability /μm	Stands mag. field
Requirements (Goals)	-	Width < 100	< 1.2	< 0.5	Yes
Precitec White Light (Precitec, n.d.)	Chr. Conf.	15×15×111	< 0.04	< 1.9*	Yes
Precitec LR (Leitz, n.d.)	Chr. Conf.	30×30×158	< 0.5	< 0.9*	Yes
STIL (STIL, n.d.)	Chr. Conf.	?	< 0.5	< 2*	Yes
TWIP (50×) (TWIP, n.d.)	Confocal	180×86×110	< 2	< 0.1*	Yes
KEYENCE LT 9011M (KEYENCE, n.d.)	Confocal	65×94×33	~ 0.4	< 1	-
Alicona IF-sensor R25 (Alicona, n.d.)	Confocal	?	~ 4	< 0.05	-
oWPS ("WPS," n.d.)	Shadow	~ 100×100×100	< 1	< 1.5	Yes
KEYENCE LS-9006D (KEYENCE, n.d.)	Shadow	360×47×260	< 5	< 0.03	-
SHARP optical switch (Sharp, n.d.)	Shadow	~ 5×5×2	A few grams	< 1.5	Yes
Fogale cWPS (Fogale, n.d.)	Capacitive	~ 70×50×50	< 0.5	< 2	Yes
LMI MicroCAD (LMI3D, n.d.)	F.P. recognition	130×55×160	1	< 2	-

* Tests performed on the PACMAN wire

Table 2-1: Summary of sensors' performances

The accuracy of the confocal technique relies on the resolution of the vertical translation system (Tiziani et al., 1996). Despite the systems available on the market show sub-micrometre repeatability, as presented in Table 2-1, the sensors are larger or heavier than the acceptable limit for the CMM. The idea of using the confocal principle directly on the probe-head was considered. Nevertheless, the vertical resolution of the CMM's translation is not suitable for the displacement of such a sensor as its increment is too large for the targeted repeatability.

A capacitive sensor could have been developed for wire measurement. Nevertheless, no company were willing to develop such a sensor for the PACMAN application.

Shadow-based sensors like the LS 9006 from KEYENCE is a good candidate for thin wire measurements. However, it is heavier than the mass limit stated for the CMM.

The company LMI 3D Technologies developed fringes recognition sensors aiming to measure small features with high accuracy. The most precise of these reaches a repeatability in the micrometric range, therefore excessively large with respect to the project's tolerances (1.3).

Chromatic confocal sensors are definitely light and small, reaching a sub-micrometre level accuracy when used in optimal conditions. As they seem appropriate for low uncertainty measurements, a comprehensive literature survey focused on nano-scale metrology performed with chromatic confocal sensors can be found below (4.5.1).

2.6 Summary and knowledge gap

The literature review presented information concerning the sources of uncertainty in CMM measurements applied to fiducialisation and revealed that:

- the absence of fiducialisation wires metrological characterisation, which is required for measurement uncertainty estimation;
- the reaction of an LSP-S4 probe-head is not reported despite the known misbehaviour of the LVDT sensors (composing it) in magnetic fields, which

may compromise the suitability of this probe-head for the PACMAN application;

- it is possible to use a chromatic confocal sensor for high precision wire measurement application;
- there is no published research demonstrating the feasibility of sub-micrometric accuracy related to non-contacting position measurements performed on a stretched wire.

From this information, a main gap of knowledge could be formulated:

- No optical sensor was adapted to a CMM on an air bearing for wire roundness measurement.

CHAPTER 3 RESEARCH APPROACH

3.1 Aim and objectives

The hypothesis of this research (see section 1.2) is that it is possible to design a sub-micrometric-accuracy form measurement sensor adaptable to a high accuracy CMM and that the increase in measurement uncertainty ensuing its additional rotary motion does not outweigh the reduction in measurement uncertainty conferred by the wire form evaluation enabled by this sensor system.

The aim of the research is to design and validate the concept of a sensor enabling the Leitz Infinity CMM to perform non-contact form measurement on the PACMAN reference wire to permit its axis positioning with an uncertainty below $0.5\text{ }\mu\text{m}$ (for a coverage factor $k=3$).

To achieve the aim of the research, the following main objectives were identified:

- determine whether the wire used to fiducialise the CLIC quadrupole magnets, accelerating structures and beam position monitor is suitable for these tasks,
- design a solution to optimally accommodate a chromatic confocal sensor to a Leitz Infinity coordinate measurement machine, within the limitations of the PACMAN project, to perform form measurement (the SESHAT),
- predict the behaviour of air pads over an opening in the bearing surface to produce a high accuracy air bearing (error budget of $0.1\text{ }\mu\text{m}$),
- demonstrate the feasibility of high precision machining of a part created by additive manufacturing,
- quantify the measurement uncertainty resulting from the use of a chromatic confocal sensor rotating around a stretched wire.

3.2 Methodology

The methodology followed the path presented in Figure 3-1.

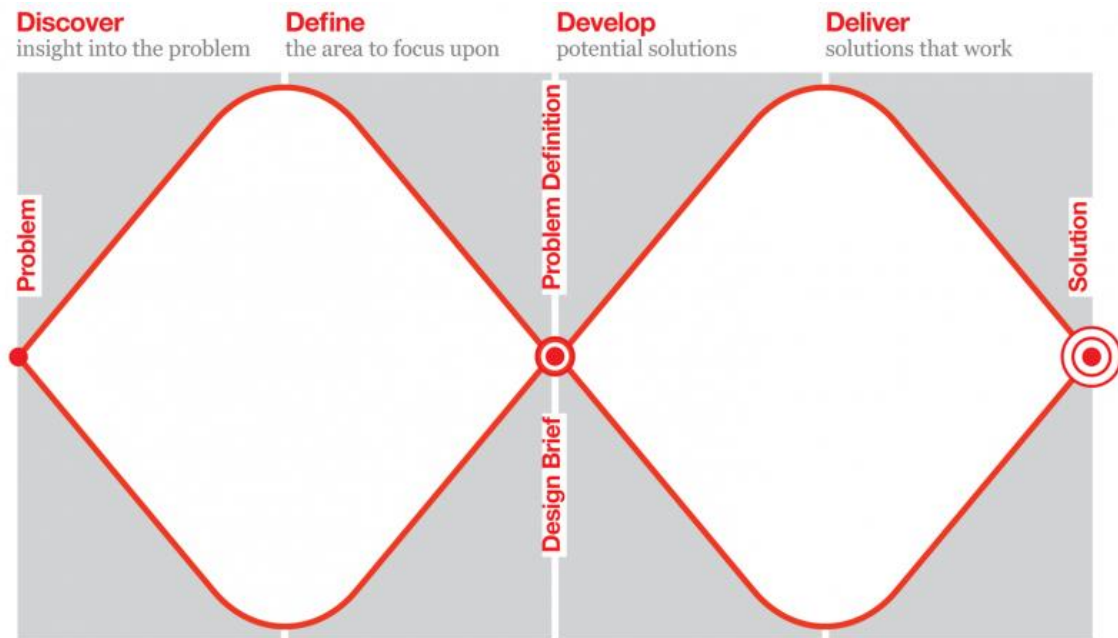


Figure 3-1: Double diamond diagram

The double diagram approach consists in broadening the knowledge about a problem, define within this knowledge the areas to focus upon and define a problem. In order to approach a solution, potential solutions are developed, among which one is preferred and finally delivered as the answer to the initial problem. Following this approach, a copper-beryllium wire with a diameter of 100 μm was chosen based on the literature review (2.4). Then, the research was to find ways of measuring the relevant characteristics of this wire in order to evaluate the quality of this reference (Appendix A). Particularly, the measurement of the roundness of the surface of such small sample was of concern (4.5). In parallel, the CMM and its LSP-S4 probe-head was evaluated within a magnetic field and approved for the project (4.2).

One of the conclusions of the wire characterisation is that the wire is non-uniform along its length (A.4.3). This observation affects the suitability of the wire for the application (4.6). The measurement techniques used by beam position monitors, accelerating structures and magnetic measurements average the wire surface roughness along its length, which averages the form error. On the contrary, the

CMM measures the wire surface on a unique line, without averaging. It was thus necessary to diminish the impact of non-negligible local feature measured on the wire surface. After evaluating the limit relevant size of such features, the decision of designing a form evaluating sensor, later named the SESHAT (Chapter 5), to be mounted on the coordinate measuring machine's probe-head, was taken.

At this stage of the thesis, the middle of the double diamond was reached and the problem defined. The next step was thus to develop potential solutions. To develop the solutions, four main research directions were treated as work packages and resulted in four standalone chapters which will present, when relevant, a literature review in the field in question, the proposed solution and the deliverable. It is appropriate to highlight that, in this research, the *solution* mentioned in the double diagram (Figure 3-1) is not a physical sensor but a design with its proof of concept and limitations.

The scope of this thesis will be limited to the knowledge leading to the development of the SESHAT (see Figure 3-1):

- the form measurement of small wire-like cylindrical features (4.5),
- the prediction of the behaviour of porous media based air pads when sliding above an opening in a surface (Chapter 6) and
- the results obtained for the micrometre-level form finishing of a rotary element obtained by additive manufacture (Chapter 7).

The second part of the methodology is the approach mentioned below and summarised in Figure 3-2:

1. Understand the motivations which led to existing techniques by analysing and studying existing processes such as
 - the chromatic confocal sensor,
 - the air pads,
 - additive manufacturing,
 - length measurement techniques.
2. Find the limitations of these techniques.
3. Find a theoretical solution to overcome these limitations.

4. Design an actual solution based on a market and literature survey, assuming that each of its elements is working as described in the literature.
5. Evaluate the differences between the actual performances and the nominal behaviours for each element of the solution.
6. Anticipate the performances of the solution with its components working according to the tests results and define what could theoretically improve them.
7. Assemble the actual solution and measure its performances, then propose future work.

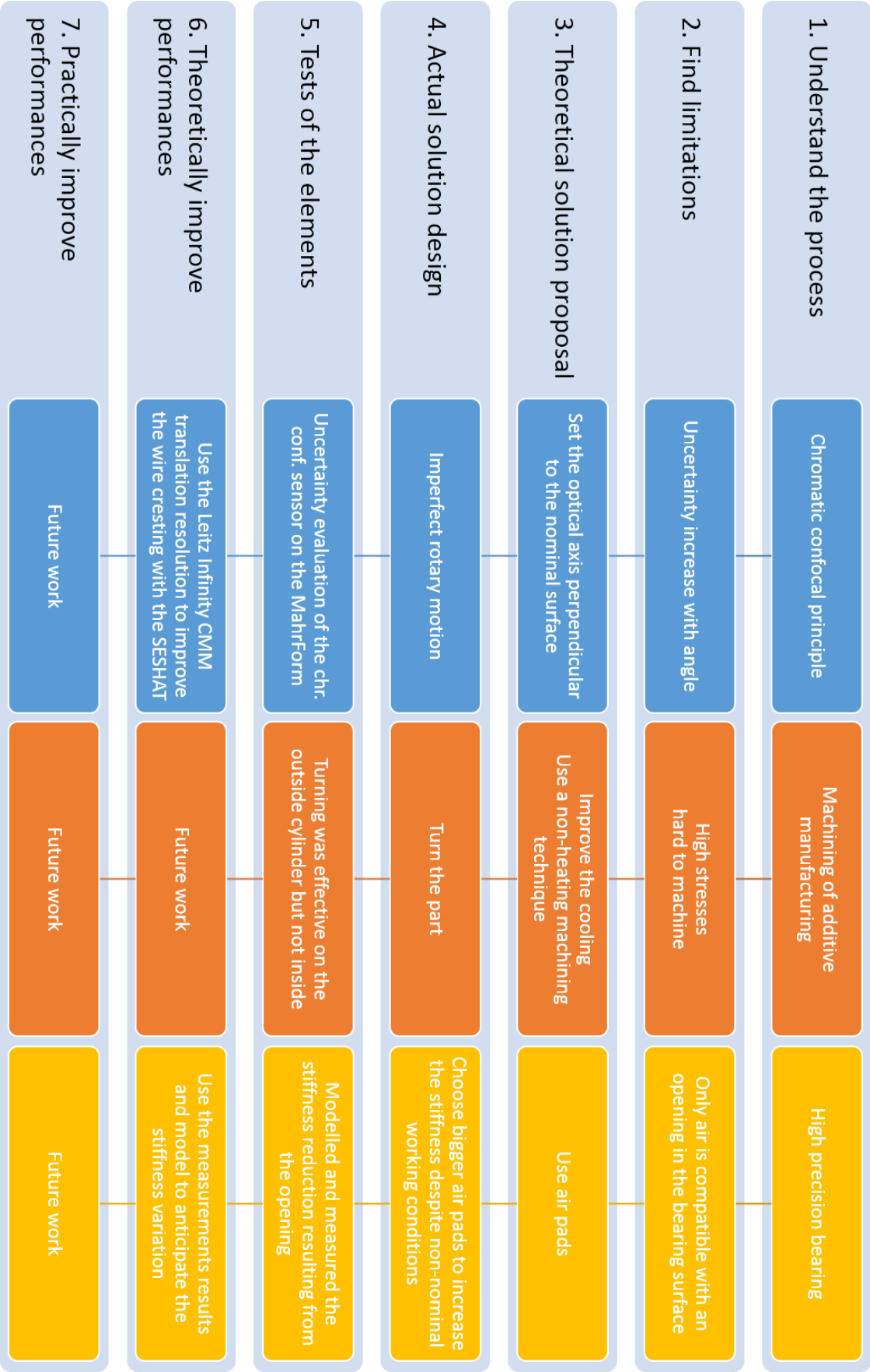


Figure 3-2: Overview of the research methodology

The literature review was used to inform points 1, 3, 4, 5 and 6 Nevertheless, gaps appeared in the literature concerning the information needed to generate nominal designs for the proposed solutions. They were covered by practical tests and they are highlighted in each of the following chapters.

3.3 Statement of originality

The author of this thesis initiated the research and participated in the development of the knowledge required to bring the results presented in this thesis, nevertheless, the work presented in this document is the result of a team work which was recognised (page iii).

Concerning wire measurements, the author

- performed the literature review
- designed the test benches and performed the measurements aiming at validating the characteristics of the wire (including its form)
- facilitated the implementation of the sensors testing setups
- performed the measurements with the Leitz Infinity CMM (Figure 1-7)
- mainly wrote the QUINDOS (4.1) scripts for the command and analysis of the measurements performed on the Leitz Infinity CMM (Figure 1-7)
- initiated and performed the measurements within a strong magnetic field
- created the Matlab script to analyse form measurement data, using existing functions

Concerning the SESHAT, the author

- initiated the concept
- chose the components
 - analysed their required specifications
 - selected them on the market
 - negotiated their prices and delivery time with the suppliers
- arranged the components on the rotor and stator
- drew the rotor's technical drawings on the paper

- decided to use additive manufacturing and high precision machining for the rotor
- decided on the rotor wall thickness for the additive manufacturing
- defined a suitable cooling technique to be applied by the technicians for the machining of the hollow rotor

Concerning the SESHAT bearing, the author

- performed the literature review on air bearings
- chose the nature, size and shape of the pads
- initiated the tests aiming at defining their behaviour above an opening
- designed the test bench setup
- partly implemented the test bench
- performed the measurements
- proposed the mathematical models for the air cushion
- wrote the Matlab scripts to predict and analyse the air pads behavioural data
- partly defined the sources of uncertainty
- performed the stiffness computations

Concerning the contribution to knowledge, the author

- Designed a novel system aiming to optimally measure the surface of a stretched wire
- Demonstrated the feasibility of micron-level form error on a complex-shaped hollow part obtained by additive manufacturing
- Proposed a mathematical model to predict the behaviour of air pads above an opening in the bearing surface and validated it against actual measurements

CHAPTER 4 WIRE MEASUREMENTS

The fiducialisation process requires the measurement of the position of a stretched wire using a CMM equipped with a non-contacting sensor. The literature review (2.4) revealed three issues related to this measurement set-up:

- The wire previously used in the fiducialisation process was not thoroughly characterised.
- A magnetic field effects on the CMM's LVDT sensors were not studied.
- There was no commercial optical sensor fitting the wire measurement requirements of the PACMAN project.

Hence, the aim of this chapter is to demonstrate that:

- the 0.5 μm tolerance on the positioning of the reference wire axis can be reached with this wire, which requires that
 - the Leitz Infinity CMM can be used within the magnetic field of the CLIC quadrupole magnet for fiducialisation measurements, and
 - an optical sensor can measure the position of the wire with a sub-micrometre repeatability.

4.1 Experimental equipment

The CMM used in this work is a Leitz Infinity CMM manufactured by Hexagon Metrology (see introduction, p.24). The CMM was operated using QUINDOS 7.

Figure 4-1 summarises the different ways in which the user can interact with the CMM using QUINDOS 7 software, introduced here:

- Quindos customers use Quindos commands to perform and analyse CMM measurements. These commands are in a high-level and user-friendly language, they can be called using small buttons with corresponding drawings in the software interface. Quindos language is translated in another language called I++ and in Leitz protocol before it is executed by the CMM.
- Some application-driven commands were made available to customers requiring more technically advanced commands, they are coded directly in I++. These are sent directly to a Leitz-Converter that translates them into Leitz-Protocol.

- The Leitz protocol is the low-level language used to control the CMM. As explained, it can be called through the I++Server using converted QUINDOS commands or I++ commands. Additionally, developers and CMM technicians can interact directly with the CMM-Interface using commands coded in Leitz protocol. These commands were used during the sensor qualification research to access both the voltmeter acquisition (which had one end connected to the controller and the other end to an optical switch) and the probe-head encoders reading.

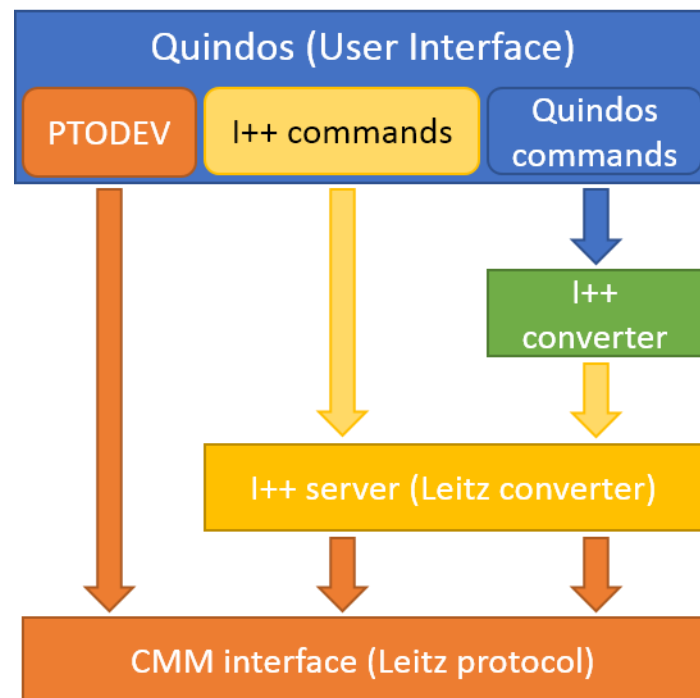


Figure 4-1: Architecture of the commands which can be sent to the coordinate measuring machine

The LSP-S4 probe-head Ultra Low Force (ULF) is a probe designed to be sensitive to ultra-low probing forces. The LSP-S4 ULF is a complex assembly comparable to the one of the standard LSP-S4 probe that is represented in Figure 4-2. The shape of the deformable parallelograms composing this assembly is altered when a force is applied on the probe tip during a contacting measurement. The flexure is measured using LVDT sensors with nanometre resolution and provides measurement data (direction of approach, applied force, position of the contact point). The ultra-low force parameter is used to increase the LSP-S4 probe-head ULF sensitivity. When activated, the CMM approaches slowly the surface and withdraws the stylus from the measured part as soon as a contact

force of 5 mN is reached. It was activated during the wire measurements aiming at evaluating the state of the art of contacting measurements (4.4.1).

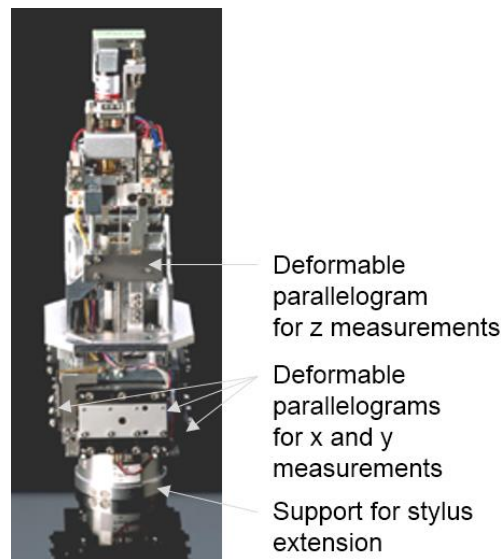


Figure 4-2: LSP-S4 probe-head

The Leitz Infinity was designed without a probe changing system; the probe is indeed inserted into the ram extremity. In order to allow for a larger variety of styli, including non-contact, the probe can be clamped and unclamped. Technically, the stiffness of the deformable assembly is increased dramatically when it is clamped, which transforms the probe into the equivalent of a ram extension by blocking the sensing part. Clamping the probe is two-fold: it helps to maintain the high accuracy of the machine despite a moving speed of 200 mm/s for long-distance displacements and it allows using the LSP-S4 probe-head to carry external probes using their independent probing system. For instance, the probing system can be a stylus system composed of an integrated chromatic confocal sensor or an external assembly using its own position control. The limit of the clamping system is that the mass of any independent probing system should not exceed 1.2 kg.

4.2 Influence of a magnetic field on the LSP-S4 ULF probe

Magnetic fields can cause undesirable effects on some mechanical parts of the probe assembly. The probe behaviour had never been assessed within a magnetic field such as the one generated by the magnet used for the PACMAN project, which can reach 0.2 T close to the magnetic pole. For these reasons, a

1.2 T strong permanent magnet has been used to create a similar magnetic field nearby the probe-head. The resulting field peaked at 20 mT near the probe, due to the fast decrease of a magnetic field in air.

Magnetic measurements have been performed directly on a Leitz Infinity CMM at HEXAGON Metrology in Wetzlar. Figure 4-3 depicts the set up used. A stylus shaft made of weakly magnetic hard metal was used. The stylus was calibrated initially using a calibration sphere in the absence of magnetic fields, then several roundness measurements of the same calibration sphere were performed within magnetic fields of different strength. The magnet was first aligned with the stylus and then aligned with the probe. All the magnetic fields have been measured with $\pm 10\%$ accuracy using a THM1176 3-axis Metrolab Hall probe (Metrolab, n.d.). The measurements were repeated and the results showed a similar in behaviour, with some variations in the measured amplitude.

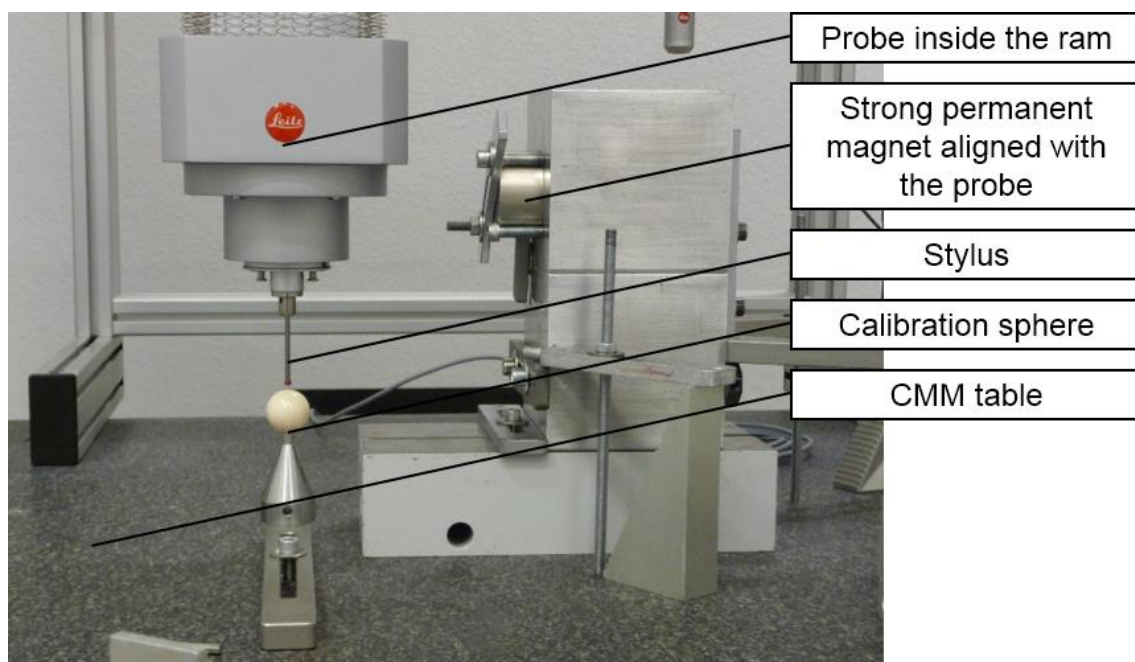


Figure 4-3: Magnetic test on the Leitz Infinity CMM

The tests were performed with the magnet aligned with the sensor and aligned with the probe-tip

The results of the tests show that:

- No change could be observed while the magnet was aligned with the stylus for a magnetic field increased up to 20 mT.

- On the contrary, the presence of the magnetic field aligned with the probe-head introduced significant errors. For example, a magnetic field of 3 mT led to few tens of micrometres of error (see Figure 4-5, b) instead of the sub-micrometric error present in normal conditions (see Figure 4-4).

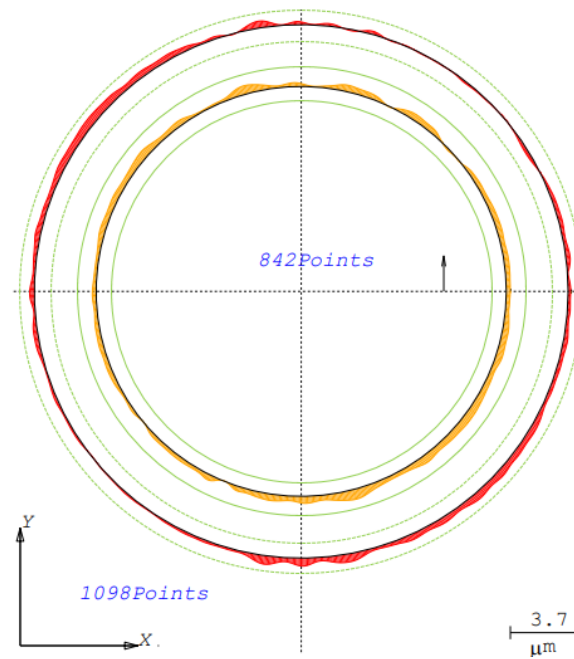


Figure 4-4: Deviation plot of the sphere before the magnetic tests

The Figure 4-5, image a, depicts a roundness test performed after the probe-head had undergone the magnetic tests. On this figure, a deviation can be observed at a position corresponding to the change of direction of the CMM's driving parts. This effect was due to an alteration of the behaviour of the damping fluid inside the head due to the influence of the magnetic field. This effect was corrected afterwards by adjusting the balance of the damping fluid in the machine's head, however, one can conclude that the machine's behaviour can be affected by a strong magnetic field. Some measurements were performed when the probe-head was clamped: in this configuration, no influence from the magnetic field on the machine's behaviour could be observed.

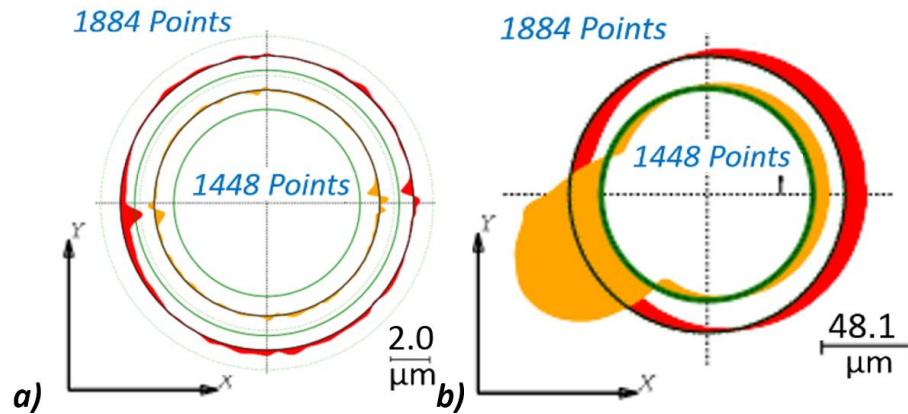


Figure 4-5: Deviation plot of the sphere
a) with 0mT after the tests were performed; b) with 3mT

4.3 PACMAN wire characteristics

The wire characteristics are summarised in Table 4-1. The results from the measurements for wires coming from two different providers (CFW stands for California Fine Wire and GF for Good Fellow) were reported in the last two columns.

Characteristics of the Ø100μm Cu-Be wire	PACMAN		Nominal Values	Measured Values	
	Min	Max		CFW	GF
Electrical resistivity [μΩ/cm ² /cm]	-	15	5.4-11.5	8.35; σ=0.02	10.86; σ=0.01
Limit tension [kg]	1	-	0.5-1.3	1.551	-
Micro-hardness [Vickers]	300	-	100-362	357	-
Linear mass [mg/m]	-	70	64.80	66.34	65.97
Diameter [μm]; variation of the diameter [μm]	90	125	100	98.5 ; σ=1.4	99.2 ; σ=0.8
Roundness deviation [μm]; variation of the deviation	-	0.5	-	2.46 ; σ=1.23	2.93 ; σ=2.04
Roughness [nm]; variation of the roughness; λ _c = 80 μm	-	-	-	20.9 ; σ=13.2	9.7; σ=5.4
Spectrometric reflectance of CFW wire					

Table 4-1: Characteristics of the Ø100μm Cu-Be wire

4.4 Probe tips for wire position measurements

The wire was measured with different probes in order to fill in the literature review gaps related to current sensors technology ability to measure small diameter objects with low uncertainty ($< 0.5 \mu\text{m}$ with $k=3$, see 3.1).

4.4.1 Contacting measurements: state of the art

The state of the art in terms of contacting measurements on a wire had to be established. To do so, a wire sample was stretched on the table of a Leitz Infinity CMM. Measurements were performed with the LSP-S4 probe-head ULF, equipped with a standard stylus with a 80 mm long shaft and a 5 mm diameter ruby ball. The controller was set to acquire 13 data points with 5 mN contact force for each measurement. A circle was fitted on the measurement points using a Gaussian fit with the software Quindos 7. However, no conclusive measurement results could be obtained. The centre of the circle fitting the wire surface could not be calculated due to the wire bending more than $50 \mu\text{m}$ under the stylus force, leading to negative wire diameter values. These results confirmed the need for a non-contacting measurement strategy.

4.4.2 Assessment of the repeatability of non-contacting probe tips on the Leitz infinity CMM

Additionally to the contacting measurement, three sensors were tested directly on the Leitz infinity CMM: two Precitec based on the chromatic confocal technique previously detailed (2.5.3) and a SHARP optical switch based on the shadow principle with an infrared light source emitting towards a phototransistor (Sharp, n.d.).

The first chromatic sensor, Precitec Lateral Resolution sensor (Leitz, n.d.), was integrated into the Leitz infinity CMM while the second chromatic sensor, a white light Precitec sensor, had a custom-made mount using an external optical fibre. Both Precitec sensors were monitored by Chrocodile controllers (Precitec, n.d.), whereas the optical switch, visible on the photos Figure 4-6, is monitored by the voltmeter embedded inside the controller. The CMM (see 2.1) was used to position the different sensors with respect to the wire.

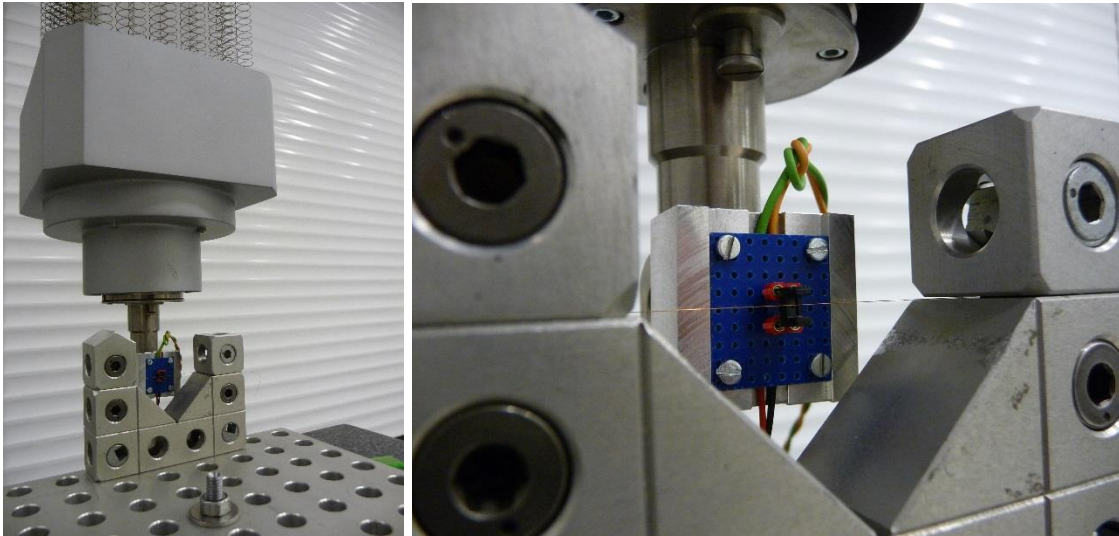


Figure 4-6: The wire on a test bench on the Leitz Infinity, being measured with an optical switch.

The first characteristic evaluated for the different sensors was the repeatability on the positioning of the centre of a circle fitted to data points acquired on the wire surface. The position of the wire centre has been measured and evaluated 100 times with the Precitec sensors and 30 times with SHARP optical switch.

Two measurements were needed for defining the position of one centre: one vertical and one horizontal (see Figure 4-7.a). For this reason, the Precitec LR set up included two sensors whereas the Precitec white light and the optical switch setups, using only one sensor, were mounted two times: in two orientations orthogonal to each other.

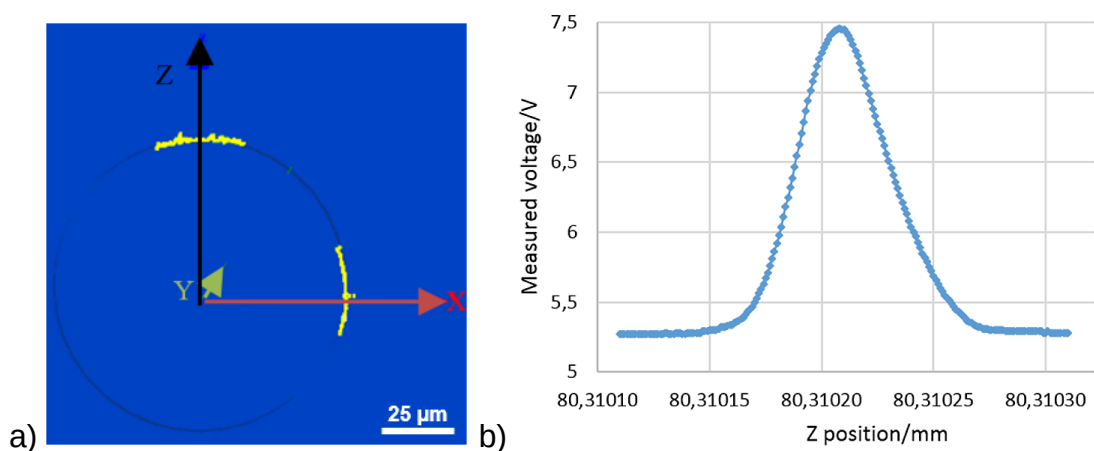


Figure 4-7: Points measured with the Precitec LR (a) and the SHARP optical switch (b)

With the Precitec sensors, the measurements were done following two steps. An initial scan estimated the position of the wire axis, which enabled to program the CMM optimal path that allowed scanning efficiently a portion of the wire.

With the SHARP optical switch probe, the wire is translated through the entire infrared beam while the controller of the coordinate measuring machine records the position of the translation stage and the voltage corresponding to the detected intensity (see Figure 4-7.b). The maximum of the recorded voltage gives the vertical or the horizontal position of the wire centre. The wire was aligned along the Y-axis so that the table holding it was as steady as possible during the measurements. As a consequence, the centre of the circles were positioned in the XZ-plane.

The results of these measurements are presented in Table 4-2.

Evaluated probe	Number of samples	3σ [μm]
Lateral Resolution Precitec sensor	100 circles	$\sigma_x=0.3$ $\sigma_z=0.2$
White light Precitec sensor	100 circles	$\sigma_x=0.5$ $\sigma_z=0.2$
SHARP optical switch	30 measurements	$\sigma=0.5$

Table 4-2: Repeatability of the sensors tested on the CMM.

4.5 Wire form measurement

Following the tests aforementioned, a chromatic confocal sensor was selected for the SESHAT. This section introduces the chromatic confocal sensor's performances and limits when applied to the wire form measurement.

4.5.1 Chromatic confocal sensors limitations

In addition to the principle of chromatic confocal sensors, which was introduced in section 2.5.3, ISO 25178-602 (AFNOR, 2010) draws a parallel between metrological properties of a contacting stylus-based sensor and of a chromatic confocal sensor as follows:

- the contacting radius of the stylus and the spot diameter of the optical probe,
- the vertical range and the chromatic confocal measurement range,
- the touching probe cone angle and the optical numerical aperture.

ISO 25178-602 (AFNOR, 2010), also mentions spurious data, which appear in the measurements results as peaks on smooth surfaces. The spurious data

should be filtered out before calculating roughness amplitude parameters such as peak to valley or before comparing results with a contacting probe.

Chromatic confocal sensors are used to perform layer thickness measurements, form measurements and texture measurements. Nourira et al. (2014) researched the error sources in chromatic confocal dimensional measurements, looking in detail to the stability of the probe, the impact of the environmental light on the results and the linearity of the confocal chromatic probe along its measurement length:

- The influence of an angle (see Figure 4-8) on the measurement results was assessed. For the white light chromatic confocal sensor with a measurement range of 20 μm , an angle up to 16 ° causes an error larger than a micrometre if the linearity correction algorithm is the same as the one used for the correction with a 0 ° angle (Nourira et al., 2014).

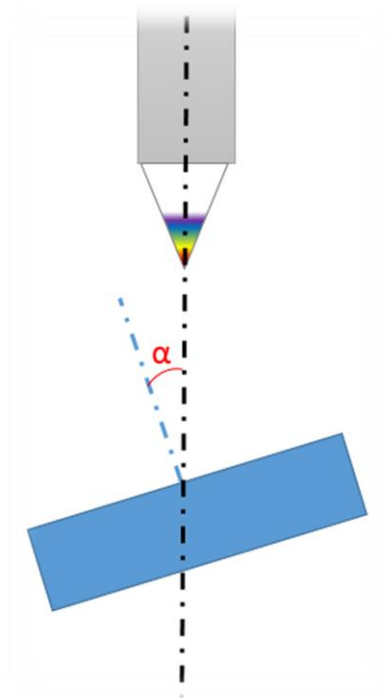


Figure 4-8: Angle α between the sensor's optical axis and the surface normal

- The scanning speed is an additional source of uncertainty with chromatic confocal sensors: it can cause errors reaching a micrometre (Nourira et al., 2014)

Characterising a grinding wheel using a chromatic confocal sensor with a measuring range of 1.2 mm was the subject of the study of Darafon et al.

(Darafon et al., 2013). The results measured with the chromatic confocal sensor were compared with the results obtained with an atomic force microscope and a contacting profilometer. The three measurement systems showed a similar trueness in the range of $\pm 0.4 \mu\text{m}$.

The chromatic confocal technique showed sub-micrometric performances for high precision on-machine measurement of an ultra-precision turning machine (Zou et al., 2017). In this article, on-machine measurement is defined as a measurement performed on a machine tool, right after machining, without removing the workpiece from its holder. An uncertainty analysis was performed and gave 83.33 nm combined standard uncertainty for the non-contact on-machine measurement. Measurements from the confocal chromatic sensor are in better accordance with contact measurements on the flat surface than on the spherical surface. In this study (Zou et al., 2017), the uncertainty contribution of the confocal chromatic probe is taken from the manufacturer's data-sheet: 12 nm, no consideration for uncertainty increase due to actual measurement conditions were made.

The design of a chromatic confocal probe entails different sources of uncertainty which should be taken into consideration. As aforementioned, the measurement range is generated by the spread of focal lengths as a function of wavelength. At a given position, the measurement light spot contains several wavelengths. Most of them are blurred and one is in focus. The light in focus after the optical elements is not a dot, it follows a point spread function. The smallest diameter of the point spread function is the diameter of the Airy disk, obtained after light traverses a perfect optical system. This non punctual spot has an averaging effect on the measurement of a surface at the micrometre scale (the spot diameter is $3.5 \mu\text{m}$ for the sensor used in this research work, as defined by the manufacturer). If the measured surface shows a local slope, several wavelengths contribute to the measurement result. Consequently, the uncertainty on the measurand is increased following the curve shown in Figure 4-9.

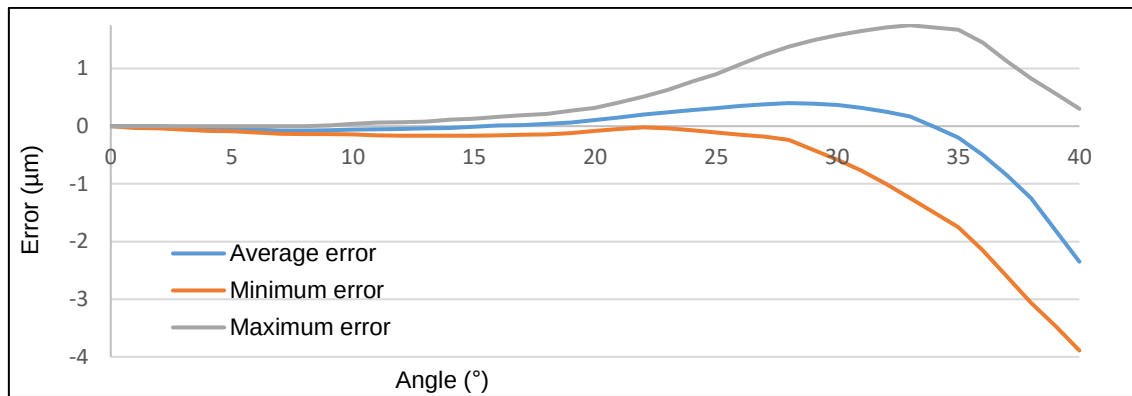


Figure 4-9: Result from the calibration of the Precitec sensor used in this research work (error due to an angle between the sensor's optical axis and the sample's surface normal)

4.5.2 Uncertainty evaluation of a non-contacting test bench dedicated to form measurement

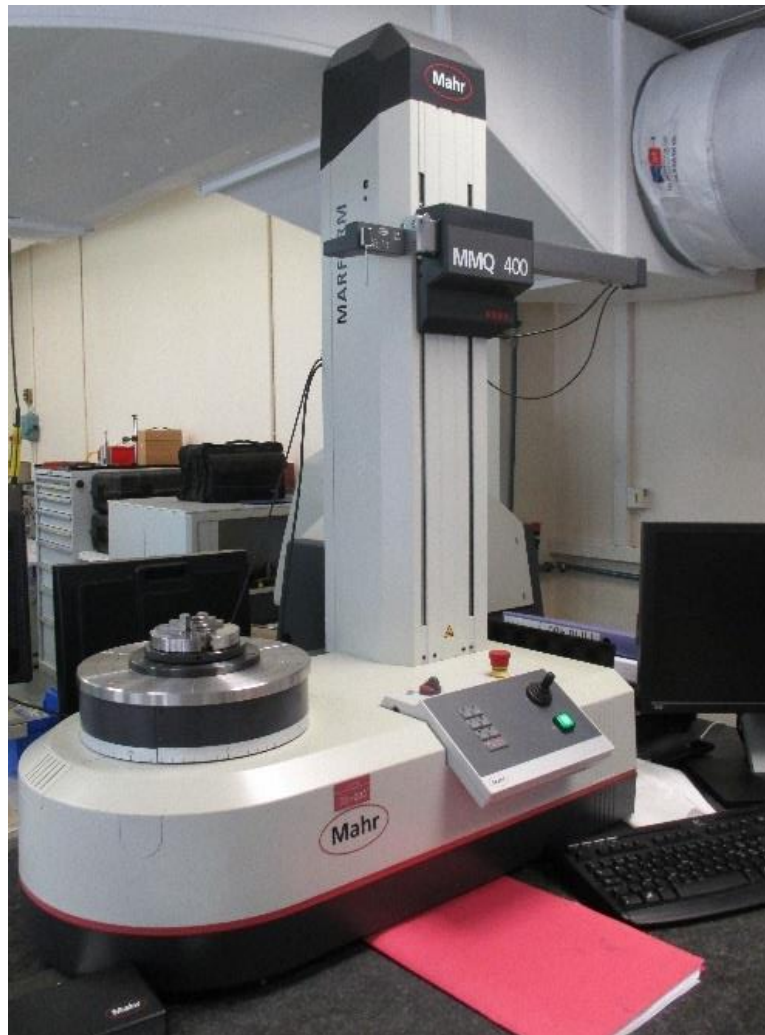


Figure 4-10: MarForm measurement device

A wire form measurement test bench was implemented based on a contacting form measurement device: the MarForm MMQ400. This system combines the use of a low uncertainty rotary table with a contacting precision sensor in order to measure roundness deviations and cylindricity deviations on rotationally symmetric samples with a sub-micrometric accuracy ("MarForm MMQ 400 - Mahr Metrology," n.d.). Each point acquired on the sample's surface is defined in a cylindrical reference system by an angular position, a distance to the centre and a height. The rotary table of this device can be used without performing a contact measurement. A wire was installed in the chuck of the rotary table and a chromatic confocal sensor was adjusted in order to measure the surface of the rotating wire. The sensor used for this application is a point chromatic confocal sensor produced by Precitec, having 100 μm measurement range and using a white light beam focused in a 3.5 μm large spot (see Table 4-3) and analysed by a CHRocodile S (see Figure 4-11).



Figure 4-11: White light chromatic confocal sensor and its CHrocodile S controller

Dimensions (Length×Diameter)	66 mm × Ø 8 mm
Numerical aperture	0.7
Mass	36 g
Spot diameter	3.5 μm
Working distance	1.4 mm
Measuring range	100 μm
Axial resolution	3 nm
Lateral resolution	1.8 μm
Axial repeatability	10 nm

Table 4-3: Precitec sensor's characteristics given by the manufacturer

The setup used to measure the roundness of the wire is depicted in Figure 4-12. In this figure, the wire mounted on the MarForm rotary table is shown with the non-contacting sensor rigidly fixed to the base via heavy iron supports and magnets. The base of the rotary table is isolated from the ground vibrations using passive damping. The wire was rotated a few times at a constant velocity while the sensor was measuring the distance to its surface.

The rotary table and the measurement acquisition system are not synchronised and the position of the table for a data point is an unknown. Thus, the wire was not aligned with the axis of rotation in order to obtain raw results with a sinusoidal shape. As a result, a sine curve could be fitted to the dataset to provide the period of rotation. Afterwards, the equation of the sine curve was subtracted from the measurement results to virtually align the two axes (Figure 9-15). An average of the few turns was used to reduce the impact of the environmental noise on the form error measurement.

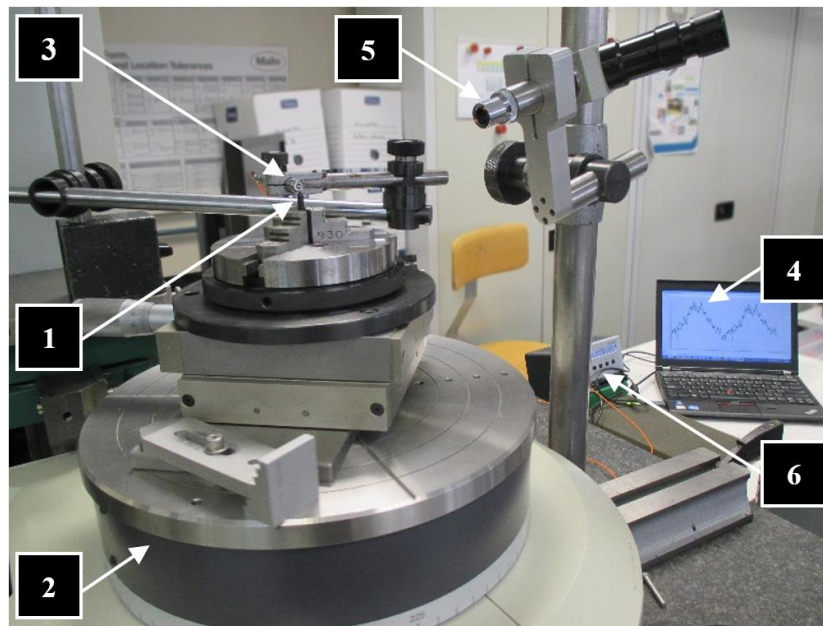


Figure 4-12: Wire measurement test bench

The sample (1) is held by the chuck on the rotary table (2), while the chromatic confocal sensor (3) is observing its surface. On the computer screen (4), the acquisition can be seen. Behind the holder of the magnifying lens used for pre-alignment (5), the controller (6) displays the acquired distance in real time.

Given the setup aforementioned, the uncertainty on the form measurement of a copper wire using the MarForm rotary table and a confocal chromatic sensor

results from the following contributions, themselves resulting from the following sub-contributions:

1. Environment
 - 1.1. Temperature
 - 1.2. Humidity
 - 1.3. Dust
 - 1.4. Light
 - 1.5. Vibrations
 - 1.6. Convection
2. User
 - 2.1. Experience
 - 2.2. Time dedicated to setup optimisation
 - 2.3. Method
 - 2.3.1. Calibration process
 - 2.3.2. Sampling frequency
 - 2.3.3. Chromatic confocal sensor operation
 - 2.3.3.1. Choice of the wavelengths within the measurement range
 - 2.3.3.2. Alignment with the part to be measured (wire crestring)
 - 2.3.3.3. Tightening of the sensor
 - 2.3.3.4. Scanning speed
 - 2.3.4. Number of repetitions during a measurement
 - 2.3.5. Post processing parameters
 - 2.3.6. Choice of the position of the circle on the surface of the sample
 - 2.3.7. Duration of measurement acquisition
3. MarForm rotary table
 - 3.1. Design
 - 3.1.1. Material choice
 - 3.1.1.1. Stiffness
 - 3.1.1.2. Thermal behaviour
 - 3.1.2. Encoder
 - 3.1.2.1. Position (Abbe error)
 - 3.1.2.2. Pitch

- 3.1.2.3. Acquisition speed
 - 3.1.2.4. Alignment
 - 3.1.3. Actuator
 - 3.1.3.1. Vibrations
 - 3.1.3.2. Heat generation
 - 3.1.4. Bearing
 - 3.1.4.1. Stiffness
 - 3.1.4.2. Bearing surface characteristics
 - 3.1.5. Form of the parts
 - 3.1.6. Damping table
- 3.2. Traceability
 - 3.2.1. Artefact
 - 3.2.2. Traceability evaluation method
- 3.3. Assembly of the MarForm
- 4. Chromatic confocal sensor
 - 4.1. Traceability
 - 4.2. Stiffness of the support
 - 4.3. Stability
 - 4.4. Sensitivity to external conditions
 - 4.5. Linearity
- 5. Data post processing
 - 5.1. Determination of the period of rotation
 - 5.2. Misalignment correction (sine removal after best fit)
 - 5.3. Approximations
 - 5.4. Filtering
 - 5.4.1. Morphological filter
 - 5.4.1.1. Hertzian contact
 - 5.4.1.2. Contact probe tip filtering effect
 - 5.4.2. Chromatic confocal measurement point effect
 - 5.4.3. Form evaluation filter
- 6. Measured sample
 - 6.1. Diameter

6.2. Reflectivity spectrum

6.3. Roughness

6.4. Form (local slopes)

6.5. Surface neatness

The sources of uncertainty affecting the form measurement which were taken into consideration in this work have been grouped into three main categories:

- the confocal chromatic sensor imperfections,
- the post-processing effects and the environmental conditions,
- the misalignment errors and the rotary table imperfections.

Each of the above uncertainty contributions is detailed in the following paragraphs. Their effect will be summarised in the form of distributions and associated standard deviations. The uncertainty evaluation was based on the Guide to the Expression of Uncertainty in Measurement (JCGM, 2008a) applied with help from the Measurement Uncertainty Analysis Principle and methods (NASA, 2010): a handbook written by the National Aeronautics and Space Administration.

4.5.2.1 Chromatic confocal sensor – traceability evaluation

Manufacturer specifications include nominal characteristics presented in Table 4-3. However, these characteristics do not account for the effects of sample intrinsic properties, such as surface roughness, reflectivity and colour, which will influence the measurement output of the sensor (4.5.1). To evaluate the uncertainty contribution of the sensor traceability combined with the effects of the wire intrinsic properties, a comparison between a contact probe and the chromatic confocal sensor has been performed.

The device used as a reference in this measurement is the MarForm evaluating device, traceable to the national standards with 50 nm of standard uncertainty after low-pass filtering (0-50 UPR). The calibration is performed using a granite cylinder gauge. The sample used for the comparison measurement is a 5 mm in diameter steel gauge. The contact probe used for the comparison has a diameter of 3 mm. The two measurements used for the comparison have been performed

simultaneously, in a temperature controlled room, by the two sensors mounted on the same base passively damped. The mounting was similar to the one shown for the 1 mm large gauge on Figure 4-13. The measurement lines were as close as possible to each other: the alignment was made with an optical magnifier comparable to the one shown in Figure 4-12, in the field of which both the light spot and the contact point of the probe-tip were visible.



Figure 4-13: Chromatic confocal sensor versus contact measurement on a 1 mm in diameter cylinder gauge (top-down view).

To perform this comparison, the results require some filtering. A Gaussian filter is chosen (equation (2-A)), it is used with two purposes:

- average the data obtained by the chromatic confocal sensor, with a cut-off wavelength equal to the diameter of the sensor's spot,
- compare the results obtained with the non-contacting probe with the results obtained with the contacting probe. To do so, the cut-off wavelength was equal to the one used by the MarForm measurement software.

The diameter of the measurement spot of the white light chromatic confocal sensor can be larger than the distance separating two points acquired on the sample's surface. Then, the Gaussian filter aforementioned, with a cut-off wavelength equal to the diameter of the spot's diameter, is applied to the measured data in order to reproduce the averaging effect of the spot diameter on

the sample's surface. As a result, the non-relevant information found within spatial frequencies higher than the spot diameter's limitation are eliminated.

A source of discrepancy between non-contacting and contacting measurements is the filtering effect of the contacting probe tip. To reproduce this effect, a morphological filter is applied. For every point, a sphere simulating the probe-tip is approached to the surface and as soon as one point of the sphere enters into contact with one point of the surface, the position of the sphere representing the probing tip the closest to the surface is logged (see Figure 4-14). The curvature of convex sample increases the distances between the peaks of its surface and decreases the distances between the valleys of its surface. In the filter mentioned, the effect of the radius of the surface of the gauge is neglected: the nominal form is considered flat instead of convex. The effect of the scanning speed limiting the access of the valleys during the contact measurement (stick-slip effect), as well as the possible effect of the sphere scratching the surface and thus reducing the height of the tops (Küng et al., 2007), are not taken into consideration in this morphological filter.

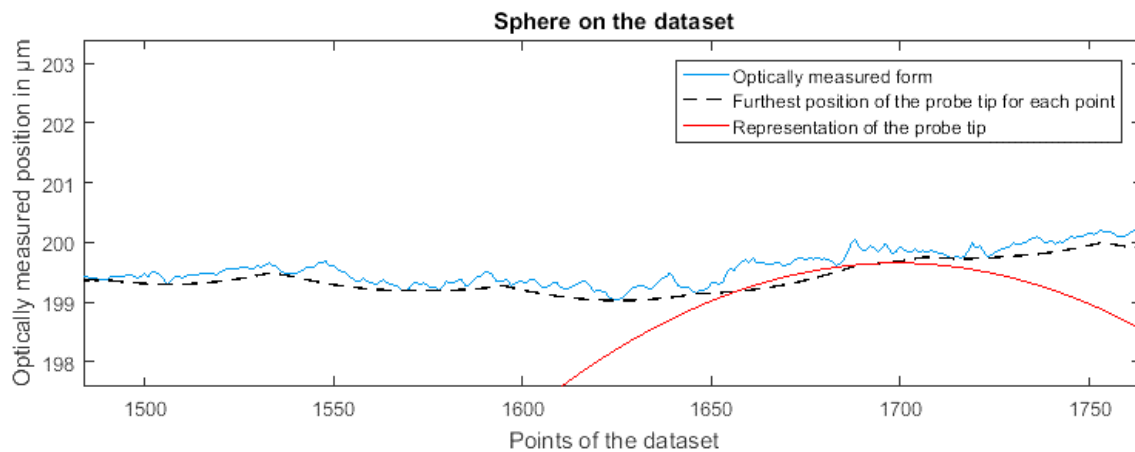


Figure 4-14: Probe filtering effect.

Chromatic confocal sensor's form measurement on a 5 mm in diameter cylinder gauge with the representation of the contacting spherical probe touching the surface and the limit reached by the extremity of the probe-tip.

During the form measurements of the 5 mm diameter cylindrical steel gauge performed with the MarForm, the contact between the 3 mm ruby probe tip and the surface of the cylinder is not a point (Budynas and Nisbett, 2015). The area of the surfaces in contact can be approximated using Hertzian theory. Using the online calculator ("Hertzian Contact Stress Calculator," n.d.) for two balls made

of ruby and steel with a contact force of 50 mN, the contact surface was found to be a disc with a diameter of 12 μm . As the real contact occurs between a cylinder and a ball, the size of 10 μm was chosen for the contact area, which determines the low pass filter cut off (see equation (2-A)), removing spatial frequencies that cannot be realistically measured with MarForm.

The sampling frequency is a source of error while comparing two datasets, as the sample with more data points will contain more information than the sample with less data points (Küng et al., 2007). As the chromatic confocal sensor acquired more points than the contacting probe, the chromatic sensor measurement was resampled to match the sampling of the MarForm.

The rotation period, obtained from matching the data with a sine equation, is validated by the user who reduces the uncertainty to 0.01 % by observing the results measured on several periods superposed in one period. The measured period length L is obtained from the diameter D by equation (4-A).

$$L = \pi \times D \quad (4-A)$$

In order to obtain the rotary period of the measurement using the algorithm developed for analysis purposes, the wire decentring must be larger than the form deviation. This causes a variation in the distance between two measurement points (see Figure 9-11), whose maximum is given by the equation (4-B).

$$Variation_{max} = \frac{2 \times decentring}{number\ of\ points\ per\ period} \quad (4-B)$$

This variation does not significantly impact the form evaluation due to the high number of data points acquired per wire revolution. Nevertheless, it is a source of uncertainty in the evaluation of the local slope of the sample's surface. Once the angular position of a measurement point is defined, the local angle α between the surface normal and the optical axis can be computed using the equation (4-C) in which $M(p)$ is the measurement result for the point p and $P(p)$ is the position on the sample's surface for the point p .

$$\alpha = \sin^{-1} \left(\frac{M(p+1) - M(p)}{P(p+1) - P(p)} \right) \quad (4-C)$$

The results of the comparison between contact and non-contact measurements show a difference of a few hundreds of microns after filtering. This is due to the non-superposition of the two measurements on the gauge surface – see discussion chapter. Using this setup and the filters described above, the system was traceable with 0.3 μm standard uncertainty (see appendix B.2).

4.5.2.2 Post-processing and environment contribution

An estimation of the environment effect on several measurements showed that it is reduced to a few tens of nanometres by controlling the room temperature and isolating the rotary table from the ground. The flow chart of the post-processing can be found in the Appendix B.

The mean of the repeatability measurement contains the information on the form. What is hereafter called *noise* is the residual after the extraction of the mean. It is composed of the confocal chromatic sensor's measurement noise, the rotary table imperfections, the environment noise and the uncertainty of the post-processing. The probability distribution of this noise is approximated as normal (see Plot 7 in Figure 9-16). As a result, its uncertainty u_{Noise} can be expressed with its standard deviation as follows in equation (4-D):

$$u_{\text{Noise}} = 160 \text{ nm} \quad (4-D)$$

A Monte-Carlo simulation based on the post-processing algorithm revealed the uncertainty on the form error evaluation as a function of the amplitude of a white noise applied to a form measurement. When using the output of this simulation as uncertainty contribution, several assumptions are done. Firstly, the noise from the environment is considered white and with a constant standard deviation during the measurement period whereas it consists in the temperature deviation and high-frequency oscillations. In other terms, it is assumed that the temperature is constant during the measurement. Secondly, the input of the Monte-Carlo simulation is the mean of a repeatability measurement. Thus, considering the output as the uncertainty for a series of measurements, one considers the form

composition of the samples of this series to not differ much from the form composition of a typical sample of this series on which was done the repeatability measurement input of the Monte Carlo simulation.

$$u_{\text{PostProcessing}} = 160 \text{ nm} \quad (4-E)$$

4.5.2.3 Contribution of the setup and alignment of the system

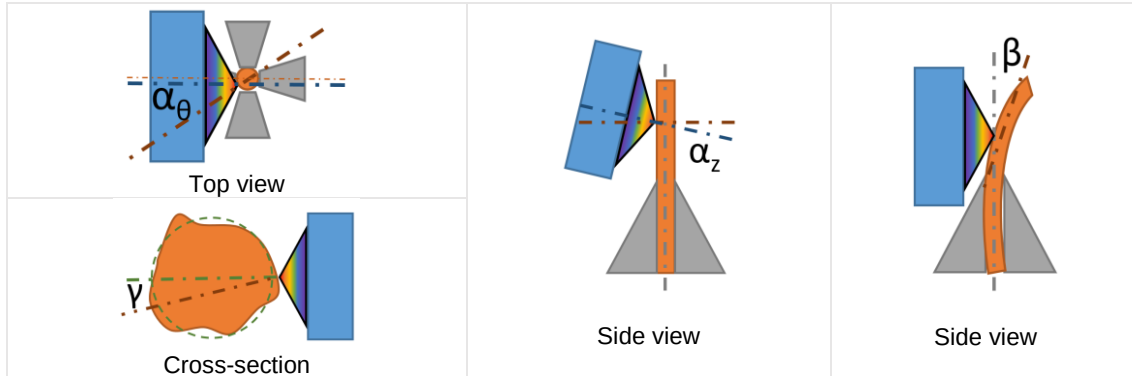


Figure 4-15: The misalignment angles

in orange the wire, in brown its actual axis or surface normal, in green its nominal shape, in grey the chuck, in blue and rainbow the sensor tip, in dark blue the sensor's axis.

The uncertainty contribution of the sensor's misalignments includes the following components:

- Angle α between the sensor and the sample's surface normal. The manufacturer provided the maximum possible error induced by the angle α for the sensor (see Figure 4-9), which includes the fact that the sensor's spot on the surface is distorted. The angle α can be divided into two components: α_θ and α_z , as follows:
 - α_z is the vertical angle. It can be easily reduced below 5° using the eye and a magnifying glass (see Figure 4-16). It increases the sensor uncertainty following the Table 4-4, and $\alpha_z = 5^\circ$ induces a negligible cosine error of 12 nm according to the equation (4-F):

$$\text{real value} = \text{measured value} \times \cos \alpha_z \quad (4-F)$$

- α_θ is the horizontal angle, which increases with the distance between the optical axis of the sensor and the wire centre (influenced by the quality of

the cresting and the sample decentring), following the sinus equation (4-G):

$$\alpha_{\theta} = \text{asin}(\text{decentring/sample radius}) \quad (4-G)$$

- Angle β between the sample local axis and the table's axis of rotation. It is taken into account in the angle α_z .
- Angle γ between the sample's surface normal and the sample's theoretical axis due to the form error of the sample (local slope). It increases locally the angle α_{θ} . This angle γ can reach 30° , so it is a large source of uncertainty in the form measurement (see Table 4-4). Nevertheless, it has a negligible impact on the form error evaluation as the extremal positions of the surface (used for form evaluation) are linked to minimal angles γ .
- Distance d between the sample's axis and the table's axis of rotation: the decentring. This distance engenders a sinewave which is removed during the post-processing.

Sensor's decentring / μm	Contribution to the angle α_{θ} / $^\circ$	Extremal error associated to this contribution to α_{θ} / μm
10	+5.7	+0.00 -0.10
20	+11.5	+0.08 -0.15
30	+17.5	+0.20 -0.15
40	+23.6	+0.76 -0.15
50	+30.0	+1.60 -0.58

Table 4-4: Variation of the misalignment angle due to the distance from the sensor's optical axis to the sample's axis for a 100 μm in diameter sample, and expression of the maximum error corresponding to such an angle α_{θ}

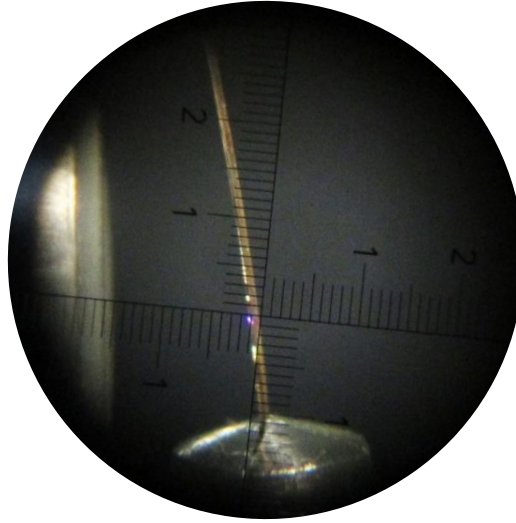


Figure 4-16: Chromatic confocal sensor's purple spot on a 0.1 mm in diameter wire with a misalignment angle approaching $\alpha_z = 7^\circ$.

During the alignment phase, special care was given to minimise the above-mentioned uncertainty contributors, so that the decentring was kept below $10\ \mu\text{m}$ and the misalignment angle α_z and α_θ were smaller than 10° .

The vertical and radial misalignment angles contribution to the measurement uncertainty (u_d) is propagated in the form of a rectangular distribution, $R(-0.13\ \mu\text{m}, 0.13\ \mu\text{m})$ that has a variance equal to $(0.13\ \mu\text{m})^2/3$.

The rotary table uncertainty is expressed by the manufacturer as the combined effect of a fixed and a measurement height dependent contribution. For the measurement configuration presented in Figure 4-12, the maximum error induced by the rotary table is estimated to approach $40\ \text{nm}$.

4.5.2.4 Total uncertainty on a non-contacting form measurement

The total uncertainty on the form measurement result u_{result} is influenced by the different sources u previously introduced, it is expressed as follows in equation (4-H):

$$u_{\text{result}} = \sqrt{\sum u^2}$$

$$u_{\text{result}} = \sqrt{u_{\text{Misalignment}}^2 + u_{\text{PostProcessing}}^2 + u_{\text{Traceability}}^2} \quad (4-H)$$

$$u_{\text{result}} = \sqrt{(75\ \text{nm})^2 + (0.0494 \times \text{form error})^2 + (300\ \text{nm})^2}$$

The average form error of $1.76\text{ }\mu\text{m}$ was acquired for a CuBe wire with a diameter of $100\text{ }\mu\text{m}$ provided by the company NGK. The uncertainty contributions presented in the Table 4-5 result from this measurement.

Source	Uncertainty /nm	Contribution /%
Traceability	300	87
Processing	87	7
Misalignment	75	6
Total uncertainty	321	100

Table 4-5: Uncertainty sources and contributions for an average form error of $1.76\text{ }\mu\text{m}$

4.6 Conclusion and discussion

The objective of the work presented in this chapter was to validate the experimental equipment proposed to measure the project reference wire. The work was divided into several tasks:

- characterise the PACMAN project reference wire,
- validate the proper behaviour of the Leitz Infinity in the measurement conditions of the PACMAN project,
- evaluate the uncertainty achieved by the chromatic confocal sensor chosen for the project on the reference wire within actual CERN laboratory conditions,
- propose an result-oriented solution for form deviation assessment.

Most of the wire characteristics, such as optical, electrical and mechanical, were easily quantifiable with low uncertainty using common laboratory's equipment. The results showed that there is little difference between wire manufacturing providers. However, the optical measurement of the surface form was negatively affected by a number of influence factors: non-optimised environmental conditions, MarForm machine limitations, wire surface characteristics and imperfect alignments.

The conclusion drawn from the PACMAN wire characterisation is that its characteristics, other than the form error, are fitting with the requirements of the project. Large and variable form error along the wire length (A.4.3) would influence detrimentally the fiducialisation process based on three point chromatic confocal sensor measurement.

4.6.1 Measurement setup

One of the limitations of the measurement set up presented in section 4.5.2 is that the combined effect of the form error and of misalignment contribution cannot be larger than the measuring range of the sensor. Nevertheless, large form errors can be measured with a non-contact sensor having a larger measuring range (which is very often linked to a larger uncertainty).

4.6.2 Traceability evaluation

Section 4.5.2 showed that a standard uncertainty of 321 nm could be reached on the PACMAN wire within the CERN laboratory environment. The chromatic-confocal measurement uncertainties dramatically increase with large misalignment angles. However, the largest uncertainty contribution comes from traceability. The contact measurement circle and the non-contact measurement circle belong to a cylinder a few tens of micrometres long. It was first assumed in this study that the 5 mm diameter lapped gauge was stable enough to be considered with the same form error for these two measurements. The results of the comparison measurements were showing discrepancies of a few hundreds of nanometres. Following this observation, measurements of 10 circles on the gauge were performed with the contact probe of the MarForm system. The results showed that the difference between two measurements separated by 15 μm can reach 150 nm before being filtered by the software. As a consequence, the large uncertainty linked to the measurement traceability may result from the non-superposition of the compared circles.

4.6.3 Further work

As mentioned in the discussion, the form measurement setup described in this study can be adapted to other form measurement of cylindrical features. The advantage of this method is that no “stitching algorithm” is needed, which eases the calibration of the sensor. A better traceability evaluation could be implemented in order to reduce the corresponding uncertainty in future uncertainty evaluations.

CHAPTER 5 DESIGN OF THE SHAPE EVALUATING SENSOR: HIGH ACCURACY & TOUCHLESS (SESHAT)

During the fiducialisation process, the relative position of the centre of the wire has to be known with an expanded uncertainty ($k=3$) that does not exceed $0.5\text{ }\mu\text{m}$. For this reason, the local roundness deviation of the wire surface, from which the centre position is derived, is to be measured with an associated standard uncertainty of $0.1\text{ }\mu\text{m}$. Additionally, the roundness measurement system has to be able to detect features with a radius of $3\text{ }\mu\text{m}$ (which is the size corresponding to an $0.5\text{ }\mu\text{m}$ displacement of the centre of a best fit circle). The literature review (2.5) revealed that there is no system fulfilling these requirements. More precisely, there is no rotary measurement system with an opening in the radial direction with sub-micron-level uncertainty on the positioning and low error motion that does not generate a magnetic field.

The SESHAT is an assembly incorporating a chromatic confocal sensor, adjusted perpendicular to the nominal surface of the wire, and a light high precision rotary mount with an opening.

This chapter describes the SESHAT, its rotary mount design and its components, which are presented in the introduction, Figure 1-8.

5.1 The sensor

After a broad literature review and market survey (2.5), the white light chromatic confocal sensor used for the wire form characterisation (see section 4.5) was chosen for the SESHAT. The main limitation of this sensor is that its uncertainty is highly dependent on the angle between the measured surface normal and the sensor's optical axis (see Figure 4-9). To overcome this drawback, the SESHAT aims at maintaining the optical axis of the sensor perpendicular to the sample's nominal surface. The chromatic confocal sensor has a high repeatability, high lateral and axial resolutions, a small size and a light mass (see Table 4-3). Several providers presented chromatic confocal sensors showing similar capabilities; the choice of the manufacturer (Precitec) was influenced by the

existing integration of the lateral resolution chromatic confocal sensor to the Leitz Infinity coordinate measuring machine (Leitz, n.d.), which would facilitate the final integration of the SESHAT on this machine.

5.2 The bearing

The SESHAT consists in a rotary element maintained within a static part, both of which have an opening in the radial direction that allows the stretched wire to go through the mount. The radial opening limited the type of commercially available bearing that could be used. The literature review and market survey indicate that the bearings used for high-quality motions are of the following kinds: cylindrical roller bearings, ball bearings, air bearings, hydraulic bearings, magnetic bearings (Boca, n.d.; Newport, n.d.; NTN, n.d.; Schaeffler, n.d.; SKF, n.d.; Standa, n.d.). The PACMAN project forbids the use of magnetic bearings (introduction, p.32)⁴. The design requirement of a radial opening in the rotor excludes hydraulic bearings with liquids and prevents any preload to be constant, making impossible the use of ball and roller bearings. Thus an air bearing were selected.

A rotary air bearing system is composed of the air pads and the bearing surfaces of the rotor. Air pads diffusing air through porous media are less sensitive to bearing surface imperfections and facilitate air flow control compared to orifice air pads, facts which increase their stability during operation. Another advantage of using millions of sub-micron-sized circular orifices for the air diffusion is that the resulting air cushion can have a thickness reduced to a few microns without risk for stopping the air flow in an area off the bearing. This is a two-fold advantage: a thin air cushion implies a high stiffness air bearing and the risk of collision between the air pad and the bearing surface is significantly reduced. Additionally, a datasheet of porous media air pads (NewWay, 2006) states that they are capable of sliding over an opening in the bearing surface, a crucial characteristic for the SESHAT application. Non-integrated air pads with porous media were only proposed by NewWay, which is why this manufacturer was preferred in this study as well as in different projects mentioned in the literature (see section 6.1).

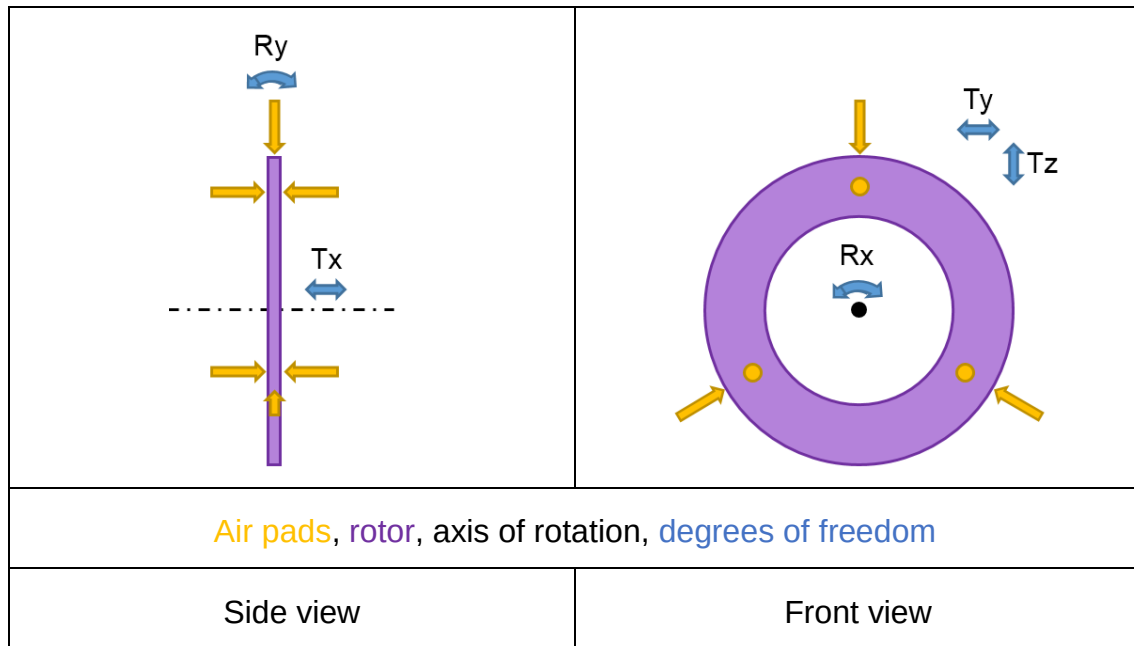


Figure 5-1: Minimum 9 air pads were needed to constrain the rotor

Toroidal air pads are not available. With the SESHAT design, minimum nine air pads were needed for the air bearing to constrain the rotor (see Figure 5-1): three pads to constrain the translations T_y and T_z and six pads (three on each side) to constrain the translation T_x and the rotations R_y and R_z . However, the bearing is designed with thirteen pads to lower the impact of the slot. Twelve air pads are mounted in opposite pairs (see Figure 5-2) in order to increase the overall stiffness without adding torques. The piezoelectric actuator (5.6) requires a preloading force of 36 N which is counteracted by the thirteenth air pad. The pairs are arranged 120° apart in order to make possible the creation of grooves on the rotor's surface. These two grooves would aim at creating a radial displacement similar to the one engendered by the slot if this latter influences critically the results. Such grooves would decrease the overall stiffness of the assembly, which is why they are not added in its nominal design.

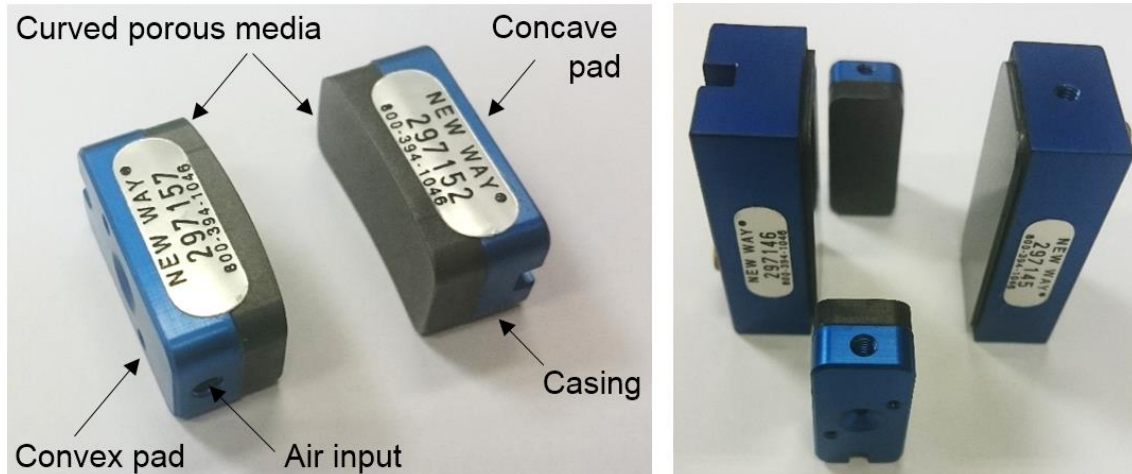


Figure 5-2: SESHAT's air pads arranged in opposing pairs

The nominal gap size for the selected air pads is 5 μm . According to the air pads manufacturer (NewWay, 2006), the form deviation of the bearing surface should never be larger than half of the gap size under the pad and that one tenth of it guarantees an optimal behaviour of the air bearing. As a consequence, the maximum acceptable form deviation, including the impact from the rotor opening, is 2.5 μm . It is added that the roughness should be regarded as part of the gap size. To ensure that it is nominally suitable, the rotor's bearing surfaces have a tolerance of 2 μm on their form (peak to valley). Nonetheless, a roundness error of the rotor peaking at 5 μm may allow for assembling the air bearing with a reduced stiffness and in non-optimal conditions.

The air pads are composed of an aluminium mount to which a porous carbon media is fixed (see Figure 5-2). This carbon media has a cylindrical shape with different curvatures, to fit with different rotor's radii. In order to reduce the delivery time, the diameters of the rotor were dictated by the off the shelf air pad curvatures. The pads alignment is particularly important for the air pads with a curvature. For this, each air pad has two screws on their side. Spherical end screws were chosen to preload the air pads, they are meant to ease the pads' alignment leading to the nominal 5 μm air gap. The air supply ensuring the pressure in the air cushion is done by air pipes.

Type (×quantity)	Dimensions (Width×Length×Height)	Radius of curvature	Load	Mass	Stiffness
Small concave (×3)	12 mm×24 mm×10 mm	96 mm	22 N	6 g	5 N μm ⁻¹
Small convex (×3)	12 mm×24 mm×10 mm	60 mm	22 N	6 g	5 N μm ⁻¹
Small flat (×1)	12 mm×24 mm×10 mm	∞	36 N	6 g	5 N μm ⁻¹
Large flat (×6)	20 mm×40 mm×13 mm	∞	111 N	26 g	14 N μm ⁻¹

Table 5-1: Air pads characteristics

The air pad's stiffness was computed from the nominal stiffness provided by the manufacturer (see Table 5-1). The pad's stiffness k_{pad} add when they are parallel and compose the stiffness in translation along the x-axis k_{T_x} , following the equation (5-A):

$$k_{T_x} = 6 \cdot k_{\text{Pad}_{T_x}} = 6 \times 14 \text{ N}/\mu\text{m} = 84 \text{ N}/\mu\text{m} \quad (5-A)$$

Nevertheless, the stiffness of the bearing assembly results from the stiffness of the air pads coupled with the stiffness of the stator. The air pads' stiffness is assured by a constant load pressing the air pads against the bearing surface of the rotor. This load is radially 44 N and axially 222 N per couple of air pads (two pads face to face), 72 N are added by the actuator and its loading air pad. This entails that the rotor should withstand this force, thus it should have a minimum axial stiffness of 222 N.μm⁻¹ to not deform more than a micrometre under the pressure of the pads.

5.3 The encoder

Two types of encoder systems exist: incremental and absolute. Incremental encoder systems start from any position and count the number of increments of the scale during a displacement. Absolute encoder systems read a unique pattern on the scale which corresponds to a unique position with respect to a reference point on the scale. Different kinds of circular encoders were considered (RENISHAW Resolute; HEIDENHAIN incremental ERA, absolute ECA...) but none of them was fitting the application for various reasons, which include: mass, no opening, too large, or the reader could not be integrated into the rotor. Thus a linear incremental optical encoder is required. A Renishaw encoder with the highest possible resolution was chosen for this application. The precision of the

positioning of the rotor may help with the compensation of systematic errors, thus reducing the uncertainty on the measurement results.

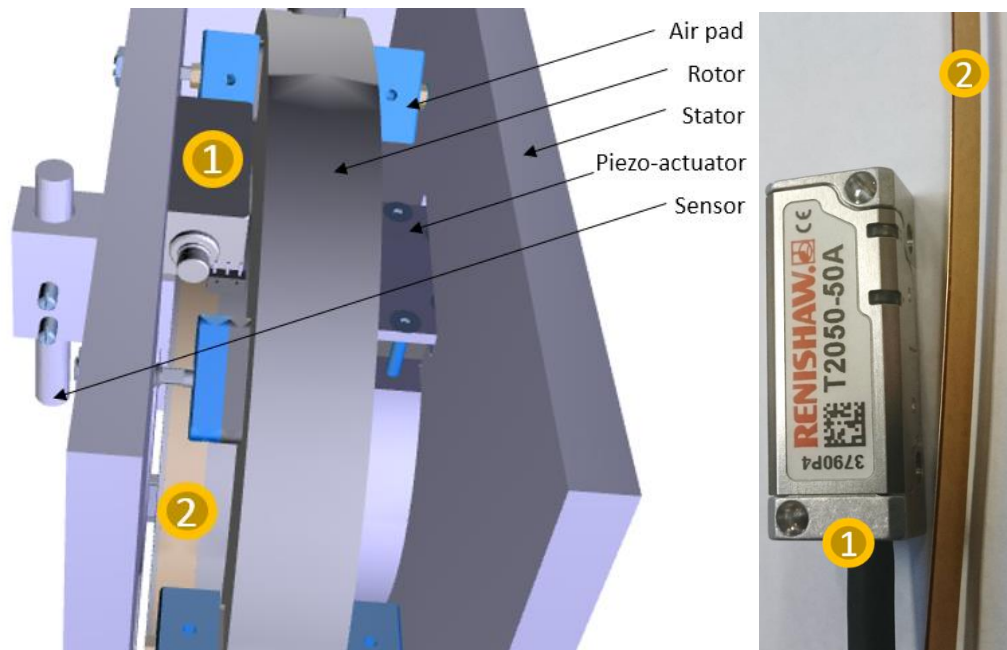


Figure 5-3: SESHAT's positioning system is composed of the encoder read-head (1) and the encoder scale (2)

This encoder is composed of a scale RGSZ20-S, which will be glued on the rotor's cylindrical surface, and a reader head TONIC ReadHead 5m RGSZ20, which will be fixed to the stator, as pictured in Figure 5-3. With the TONIC Interface X20KD, an electronic integral interpolation can be performed in order to improve the resolution in the positioning of the rotor to 1 nm (according to the manufacturer). Only this configuration of the encoder system is compatible with an open shaft. The encoder is connected to the piezoelectric actuator's motherboard, allowing the position control in closed loop. A limit position will be set to prevent the actuator from encountering the slot in the shaft.

Dimensions (Width×Length×Height)	13.5 mm×35 mm×10 mm
Minimum scale bending radius	200 mm
Scale Linearity	± 750 nm / 60 mm
Scale pitch	20 µm
Read-head mass	10 g
Required surface roughness of the substrate	Ra < 3.2 µm
Max speed	13 mm.s ⁻¹

Table 5-2: Renishaw encoder characteristics

The encoder read-head is mounted opposite the piezoelectric actuator, which increases the circular measuring range of the SESHAT. The measurement speed

is limited by the encoder. In order to obtain the highest possible precision with this encoder system, the speed should not exceed 1/30 rpm. The encoder must be validated as compatible before being incorporated into the SESHAT, as the bending radius required is half the minimum bending radius approved by the manufacturer.

5.4 Rotor and stator material

Successful design for high precision applications requires optimal material selection (*ASM handbook*, 1990a; *ASM handbook*, 1990b). The material requirements for SESHAT's rotor and stator are:

- high stiffness: final rotor stiffness $> 222 \text{ N } \mu\text{m}^{-1}$,
- light: final rotor mass $< 0.5 \text{ kg}$,
- low thermal expansion coefficient,
- non-ferromagnetic,
- non-porous in front of the air pads,
- hard in front of the piezoelectric actuator: hardness $> 1400 \text{ Vickers}$,
- possible to machine to a micrometre-level geometrical accuracy and a sub-micrometre level roughness.

Hardness in front of the piezo-actuator larger than 1400 Vickers indicated the use of a material at least as hard as alumina ceramic. Nevertheless, alumina could not be machined to the accuracy required for the air pads within the period and financial constraints imposed by the project. Thus, the alternative solution, which was chosen, was to manufacture the rotor from a material easier to machine with precision and use an alumina ring insert to be compatible with the actuator. However, the rotor material's thermal coefficient of expansion had to be close to the one of alumina ceramic in order to prevent unwanted distortions during cooling and warming up cycles of the rotor.

Aluminium had good ductile properties and Scalmalloy, an aluminium alloy, had improved stiffness, but their coefficients of thermal expansion did not match the one of Alumina. Silicon was too fragile, Carbon Fiber Reinforced Plastic (CFRP) was very light and stiff but had a non-isotropic mechanical behaviour that did not

fit a rotational application. Bamboo and carbon had similar problems to CFRP with added issues related to the surface roughness and porosity. Granite had good matching properties, however, the shape of the rotor required a long manufacturing time that was outside the time constraints of the project. As a result, Titanium was chosen for the final version of the rotor as its thermal expansion coefficient, $CTE_{Ti} = 8.6 \mu m.K^{-1}$, was approaching the one of ceramic, $CTE_{Al_2O_3} = 7.6-8.4 \mu m.K^{-1}$.

Additional tests were required to determine whether all the aforementioned tolerances of the project on the rotor form could be reached, particularly, whether the machining tolerance and mass limit would be exceeded with a titanium rotor. With a density of $4.42 kg/dm^3$, a plain Ti-6Al-4V rotor would be heavier than the 0.5 kg. However, Titanium alloy can be shaped with all the freedom of additive manufacturing and thus its mass can be reduced. The ability of machining titanium additive manufacturing components to the micrometre level is discussed in chapter 7.

5.5 The rotor

As stated in the introduction, the rotor is a key element of the SESHAT because it carries the optical sensor. The encoder scale is glued to the rotor and four of the rotor's surfaces, appearing in Figure 5-4, compose the air bearing (see section 5.2). The shape of the rotor results from a compromise aiming at ensuring that each component of the assembly functions at best. As the rotor is produced using an additive manufacturing technique, its design should allow for the powder removal.

The design of the rotor was aiming at reducing the Abbe offset: the encoder scale is as close as possible to the sensor's measuring point. Nevertheless, space was needed for the air pads to be assembled with the stator, which implies an Abbe offset of a few millimetres (see 5.10).

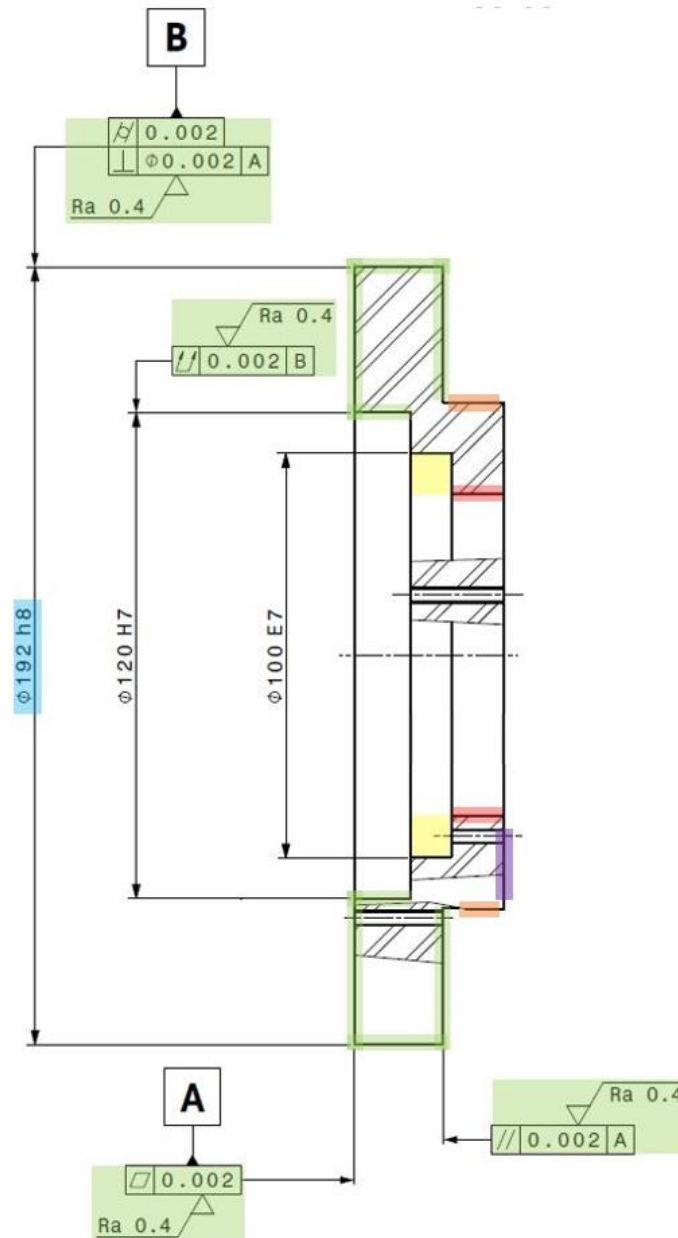


Figure 5-4: Rotor's technical drawing and its functional parts.

In green the bearing surfaces, in yellow the indentation for the alumina ring, in red the grid wall for powder removal, in blue the largest length making the manufacture and machining challenging, in purple the area tightening the sensor, in orange the face to glue the encoder scale.

The rotor's maximum momentum of inertia amplitude (I), given by the computer-assisted drawings software, is 7 g m^2 . The actuator should be installed at a distance (d) equals to 45 mm from the rotation axis. The angular speed (ω), dictated by the encoder (section 5.3), is $\pi/15\text{ rad.s}^{-1}$. Therefore, the actuator's force (F) should be larger than 7 mN , according to the equation (5-B):

$$F = I \cdot \frac{\omega^2}{d} = \frac{7 \times 10^{-3} \times \pi^2}{15^2 \times 45 \times 10^{-3}} \text{ N} = 6.8 \text{ mN.} \quad (5-B)$$

5.6 The actuator

The actuator chosen for the application is a HR2 actuator from Nanomotion. It is based on the piezoelectric principle and fulfils the following requirements at best:

- as light as possible,
- as small as possible,
- strong enough to control the rotation of the rotor,
- not affected by magnetic fields,
- not creating any magnetic field,
- generating as little heat as possible.



Figure 5-5: HR2 Nanomotion piezoelectric actuator

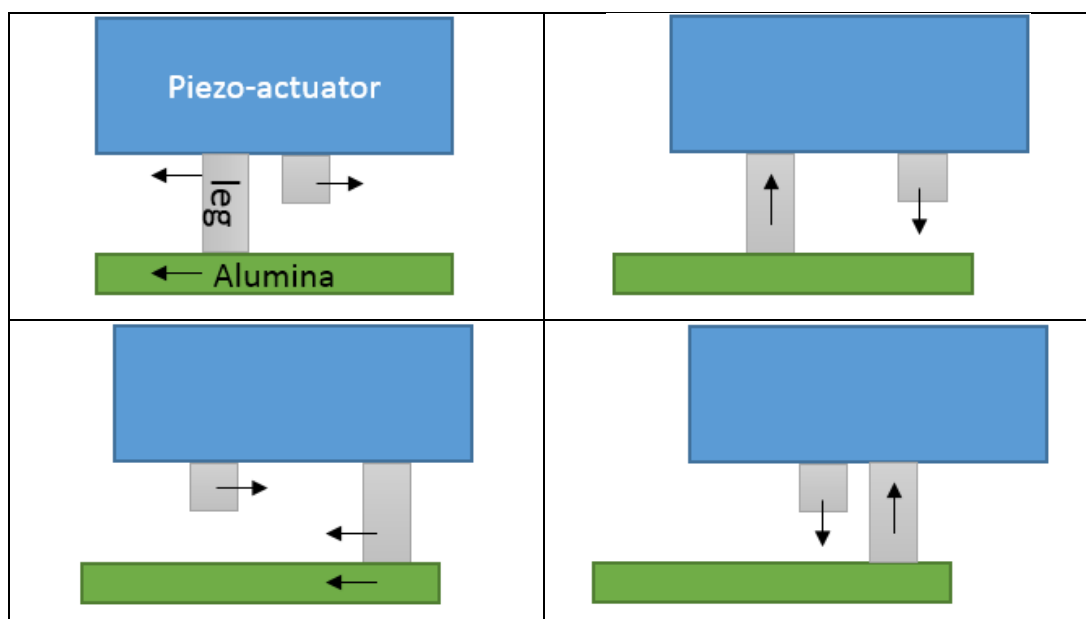


Figure 5-6: Principle of the motion of a piezo-actuator with two legs.

A piezoelectric material is able to generate a voltage when being deformed and to deform when receiving a high voltage. The working principle of the selected piezoelectric actuator (see Figure 5-5) is based on the friction between a piezo ceramic leg and a hard surface. The motherboard, the controller, adjusts the input voltage so that a leg moves from front to back touching the surface against which it is preloaded and goes back to the front without touching this surface (see Figure 5-6), with a frequency of 40 kHz. The motherboard adjusts the actuator's speed by changing the amplitude of the legs displacements. The drawback of piezoelectric actuators is the strong preload and the high stiffness required for the surface on which it is applied. Additionally, vibrations of the bearing surface under the actuator's legs can lead to the destruction of the legs.

Volume (Width × Length × Height)	12.7 mm× 40.5 mm× 25.7 mm
Static stiffness	1.8 N μm ⁻¹
Force	7 N
Mass	60 g
Nominal preload	36 N
Max speed	250 mm.s ⁻¹
Maximum resolution	100 nm
Requirement on stiffness	> 100 N/μm

Table 5-3: HR2s piezoelectric actuator characteristics

5.7 The stator

The stator final design is not covered by the content of this thesis due to the limited time frame of the project. Nevertheless, a few design concepts and their results are presented in this section after an introduction to the role of the stator.

The role of the stator is to hold in place all the elements constituting the SESHAT. The stator must have a maximum width of 90 mm and be stiff and light. No high precision manufacturing is required for the stator but it should have good thermal properties: predictable or negligible deformations, or deformations with a reduced impact on the measurement results. To reduce the impact of the thermal deformations, the stator should be as symmetrical as possible with respect to the piezoelectric actuator (source of heat) and the air pads (source of cold). As a result, the holder plate stands opposite the opening.

After a functional design initially made of aluminium to optimise the thermal diffusion, depicted in Figure 5-7, carbon sandwich panels and peek were considered in order to remove the concerns with the mass limit, as appears in Figure 5-8 and in Figure 5-9. Results of simulations with the nominal load from the air pads pushing on the carbon-peek structure are presented in Figure 5-9. They show that the stiffness of the designed stator was not sufficient for the air pads: the deformation could not assure proper working conditions for the air pads.

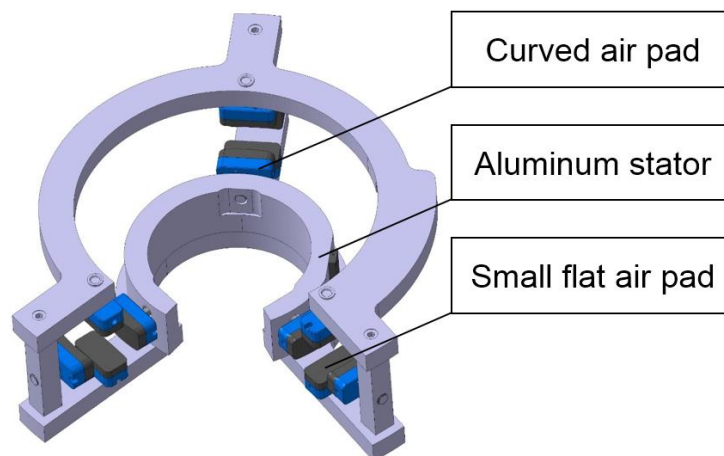


Figure 5-7: First version of the aluminium stator for the SESHAT

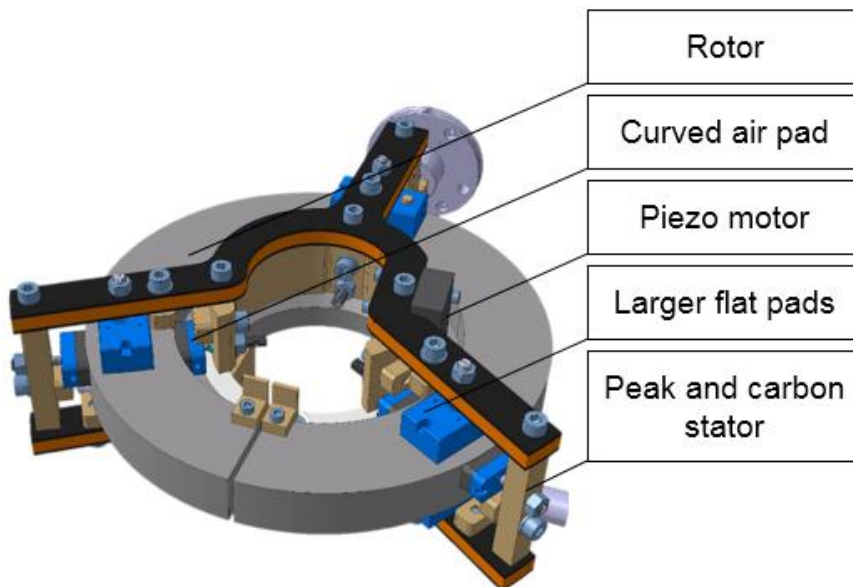


Figure 5-8: The SESHAT with a light carbon and peek stator

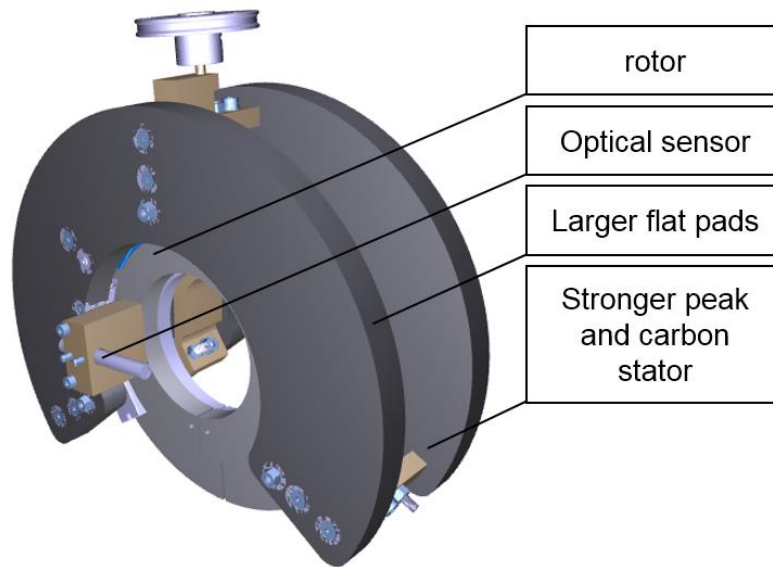
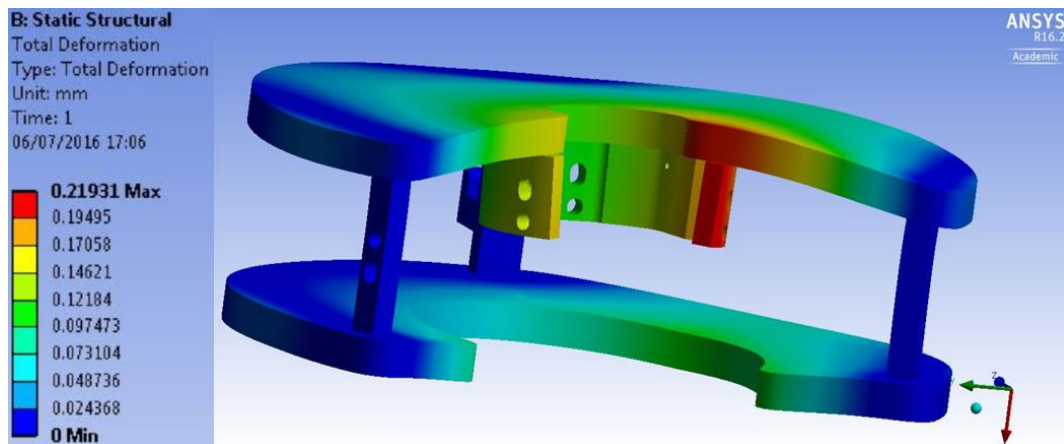


Figure 5-9: Enlarged carbon stator and its maximum deformation.
 The simulated stator reaches 219 μm of deformation under the 222 N of pressure applied by the air pads: this design cannot be used for the high precision bearing assembly required for the SESHAT

Considering these results, a 'test bench stator' was designed to stand on a table (vertically or horizontally), made out of plain thick aluminium (see Figure 5-10). The final version will require more investigations like the optimisation of an additively manufactured titanium part.

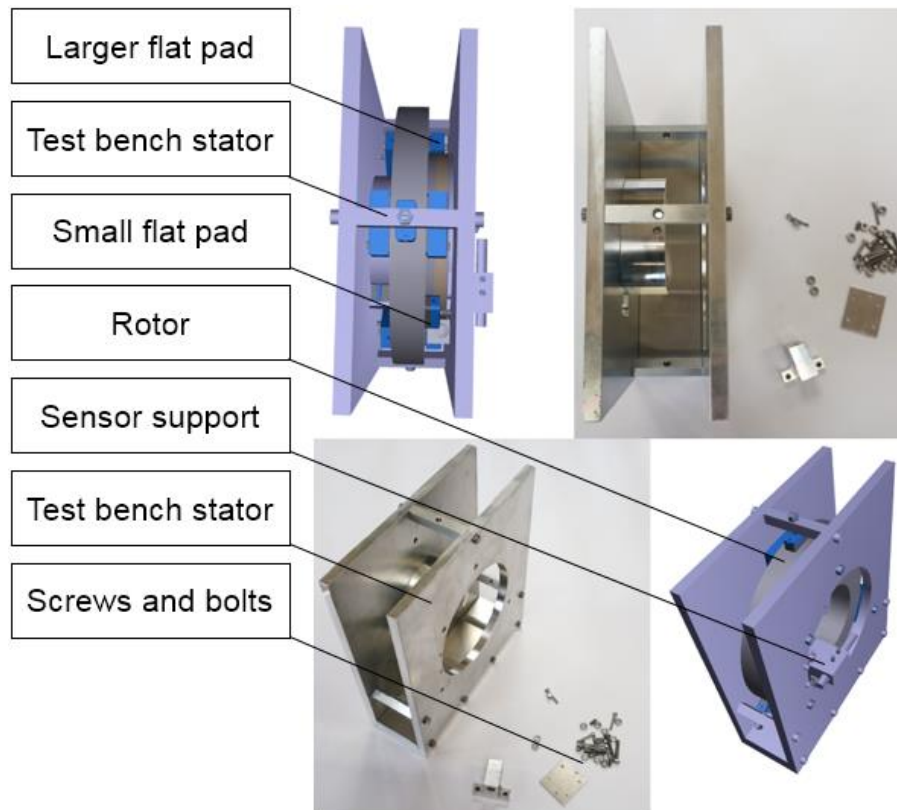


Figure 5-10: SESHAT's stator test version

5.8 End-course protections

Three protection elements are in place to prevent the actuator to reach the slot in the rotor and break:

- a software protection: the actuator stops when a limit position is read by the encoder (5.3);
- an electro-mechanical protection: end course sensors and
- a physical protection: mechanical end stops.

The end course sensors are small electro-mechanical elements that send an electric signal, when pressed, to the actuator's motherboard, that orders to stop the actuator. The end course sensors chosen are AV4 miniaturised switches from Panasonic, having a mass of 0.2 g, featuring the dimensions appearing in Figure 5-11.

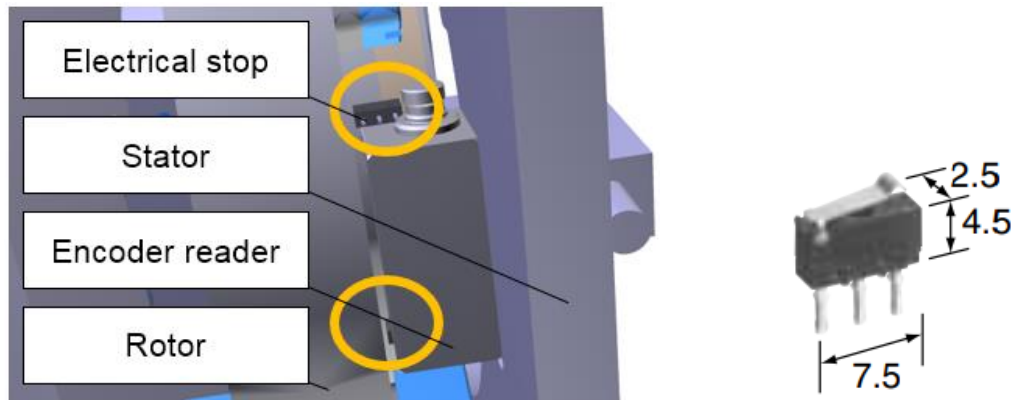


Figure 5-11: SESHAT's end course switches with the photo of the switch and its dimensions in mm

The mechanical stops are two screws with large heads tightened to the rotor, which are designed to enter in contact with the encoder read-head and mechanically block the rotation when necessary.

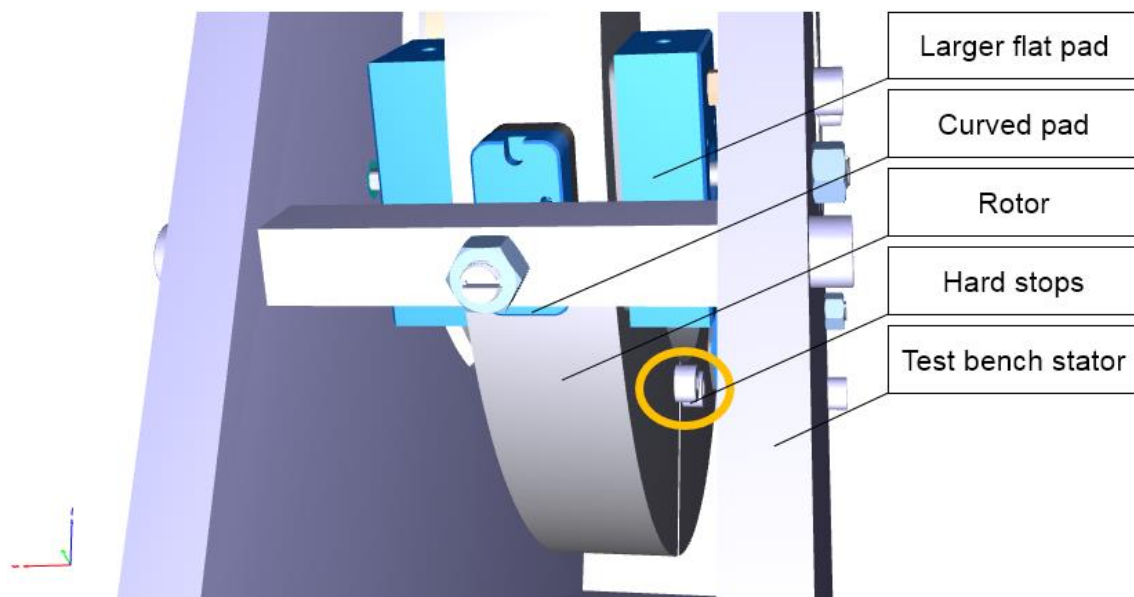


Figure 5-12: SESHAT's mechanical end stops

5.9 The SESHAT in numbers

The following Table 5-4 recapitulates information concerning the SESHAT components and assembly.

Actuator's minimum force (5.4) due to rotor's inertia*	7 mN
Actuator's dynamic stall force**	7 N
Rotor's mass (5.4)	450 g
Air pad's mass**	198 g
Sensor's mass**	36 g
Actuator's mass**	60 g
Encoder's read-head mass**	10 g
Other components' mass (screws, ...)*	~100 g
Max mass admissible on the clamped probe-head**	1.2 kg
Requirement for SESHAT's stator's mass	< 320 g
Sensor's spot diameter**	3.5 μm
Sensor's working distance**	1.4 mm
Sensor's measuring range**	110 μm
Requirement on feature's size to be measured by the SESHAT	6 μm
Requirement on width for the SESHAT	< 100 mm
Actuator's requirement on axial stiffness**	> 50 N/ μm
Air pad's axial stiffness (5.2)**	84 N/ μm
Requirement on stator's stiffness in radial directions	> 5 N/ μm
Requirement on stator's stiffness in axial direction	> 17 N/ μm
Aluminium test bench axial stiffness (beams)*	363 N/ μm
Resolution of the encoder (interpolated)**	1 nm
Positioning resolution of the actuator**	100 nm
Temporal requirements	none
Approximated time needed for one measurement	~30 s

* From CAD software

** From manufacturers' data sheets

Table 5-4: SESHAT's characteristics

5.10 SESHAT uncertainty contributors

The uncertainty on the positioning of a sample within the CMM's measurement volume using the SESHAT as a sensor results from the following contributions, themselves resulting from the following sub-contributions:

1. Environment
 - 1.1. Temperature
 - 1.2. Humidity
 - 1.3. Dust
 - 1.4. Magnetic field
 - 1.5. Light
 - 1.6. Vibrations
 - 1.7. Convection
2. User
 - 2.1. Experience
 - 2.2. Time dedicated to setup optimisation
 - 2.3. Method
 - 2.3.1. Calibration process
 - 2.3.2. Filtering parameters
 - 2.3.3. Sampling parameters
 - 2.3.4. Chromatic confocal sensor operation
 - 2.3.4.1. Choice of the wavelengths within the measurement range
 - 2.3.4.2. Alignment with the part to be measured
 - 2.3.5. Number of measurements
 - 2.3.6. Choice of the position on the sample surface
 - 2.3.7. Duration of measurement acquisition
3. SESHAT
 - 3.1. Design
 - 3.1.1. Material choice
 - 3.1.1.1. Stiffness
 - 3.1.1.2. Mass
 - 3.1.1.3. Behaviour in magnetic fields
 - 3.1.1.4. Thermal behaviour
 - 3.1.2. Encoder
 - 3.1.2.1. Position (Abbe error)
 - 3.1.2.2. Pitch
 - 3.1.2.3. Acquisition speed

- 3.1.2.4. Alignment
- 3.1.3. Actuator
 - 3.1.3.1. Vibrations
 - 3.1.3.2. Heat generation
- 3.1.4. Air bearing
 - 3.1.4.1. Opening
 - 3.1.4.2. Stiffness
 - 3.1.4.3. Cooling effect
 - 3.1.4.4. Input air characteristics
 - 3.1.4.5. Bearing surface characteristics
- 3.1.5. Wires and cables tightening
- 3.1.6. Tolerances
- 3.1.7. Chromatic confocal sensor
 - 3.1.7.1. Alignment (within the SESHAT assembly)
 - 3.1.7.2. Traceability
 - 3.1.7.3. Stiffness
 - 3.1.7.4. Stability
 - 3.1.7.5. Sensitivity to external conditions
 - 3.1.7.6. Linearity
- 3.2. Traceability
 - 3.2.1. Artefact
 - 3.2.2. Traceability evaluation method
- 3.3. Assembly of the SESHAT
- 4. CMM
 - 4.1. Positioning
 - 4.1.1. Resolution
 - 4.1.2. Stability
 - 4.2. Head clamping
- 5. Data post processing
 - 5.1. Misalignment correction
 - 5.2. Motion bias compensation (mapping)
 - 5.3. Roundness evaluation

- 5.4. Sag/straightness compensation
- 5.5. Approximations
- 6. Measured part
 - 6.1. Diameter
 - 6.2. Reflectivity
 - 6.3. Roughness
 - 6.4. Form
 - 6.5. Surface cleanliness
 - 6.6. Sag when relevant

The contributions to the SESHAT measurement uncertainty were not quantified yet, this should be done in the future. Nevertheless, the design of the SESHAT anticipated some needs and aimed at, for instance, the minimisation of the Abbe offsets within the other constraints (see Figure 5-13). The encoder could not be positioned closer to the sensor's tip due to the minimum bending radius of the encoder scale (see 5.3). Nevertheless, the Abbe error is not a major source of error in the design of the SESHAT. The measurement is performed by the chromatic confocal sensor, which is aligned with its measurement point. The influence of the motion imperfections is direct on the measurement results, as the imperfections will change the distance between the sensor and the wire surface. The influence of the position read by the encoder will affect the regularity of the distribution of the measured points, as a result it would influence the form evaluation by influencing the best fit of the circle applied to the results, this error is estimated to reach a few tens of nanometres only. Furthermore, the incremental encoder is redundant with the piezo motor if used as a stepping motor, as both can measure the displacements. The Abbe offset has thus a negligible impact on the form evaluation results.

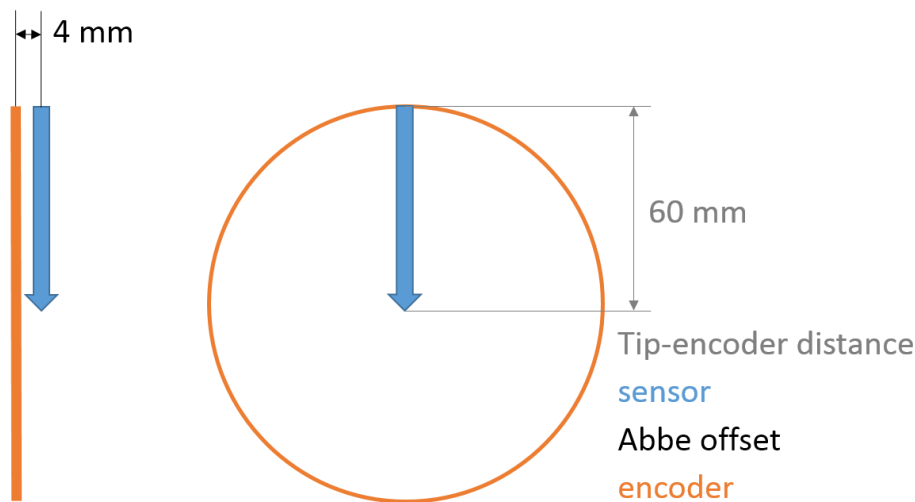


Figure 5-13: Alignment of the measurement point with respect to the encoder.

The overall aim of the SESHAT is to reduce the measurement uncertainty on the wire axis positioning. However, the bearing residual degrees of freedom will increase the measurement uncertainty. The bearing contributions to the measurement uncertainty will be reduced by:

- an increased stiffness (thus a small air gap),
- cleaned and temperature stabilised air inputs, and
- low bearing surface roughness and waviness.

All the components of the SESHAT assembly must be assembled with care. For instance, the heat generated by the piezoelectric actuator will diffuse into the assembly through the larger areas that are in contact with the actuator casing and thus benefiting from a greater surface to cool rapidly by air convection. The vibrations produced by the piezoelectric ceramic legs of the actuator will dissipate through the assembly without being amplified by loose components.

5.11 Stability of the SESHAT

The short-term stability of the components of the SESHAT was guaranteed by the manufacturers of these components. Nevertheless, SESHAT long term stability needed to be ensured. As a result, the ceramic ring inserted into the rotor is screwed and glued, the glue being assured by the manufacturer as stable in time. Additionally, the resonance frequency of the ceramic ring was checked to be theoretically impossible to reach during the operation of the piezoelectric

actuator, whether there is a slot or not (the resonance frequency is not the same with and without the slot, for an alumina ring bound to the rotor, it is theoretically 475 Hz). As mentioned (5.4), the materials were carefully selected to behave in similar ways, thus reducing the risk of incompatibilities leading to a premature wear of the parts.

5.12 Conclusion and further work

This chapter has introduced the design of the SESHAT, which is a novel high precision measurement system that incorporates an open rotor and allows for stretched wire form evaluation.

The SESHAT features:

- An encoder,
- A rotor,
- A piezoelectric actuator,
- A stator,
- End course sensors and mechanical stops,
- A bearing with a radial opening for a stretched wire to go through.

The main technological gaps were identified to be:

- the behaviour of an air bearing over a slot in the bearing shaft and
- the precision machining of a titanium part obtained by additive manufacturing with form errors below 2 μm .

Additionally, no report mentions assembling a HR2 piezoelectric actuator with an air bearing.

5.12.1 Further work

Some components of the SESHAT were not fully tested (end-stops, some air pads, the encoder after bending the scale). The computer assisted model includes no cabling of the different elements. The electrical wires (piezoelectric actuator, end-stops, encoder), the air pipes (13 pads) and the optical fibre (sensor), as well as their connection parts when needed, require being properly integrated into the design.

The SESHAT needs to be assembled on the prototype stator and tested. The influence of the piezoelectric actuator on the measurements has to be tested in order to determine whether the data points can be acquired during the rotation or requires the rotor to stand still. Based upon the results, a proper stator should be designed, assembled, tested and weighted with all the elements before being installed on the CMM. All the wires and pipes aforementioned may require being tightened to the Leitz Infinity ram in order to avoid overweighting the assembly. The software integration will have to include the calibration process for the sensor and a software compensation of the systematic errors brought by the additional degree of freedom.

Further work would include creating a user manual and a training program for the operator.

CHAPTER 6 BEHAVIOUR OF SMALL DIMENSION AIR PADS ON A HOLE

SESHAT bearing system (see section 5.2) is composed of porous media air pads. The tests presented in this chapter aim at validating that the air pads are suitable for the SESHAT application: capable of sliding over an opening with a predictable behaviour and a sufficient stiffness. In other words, the hypothesis that a high precision low speed air bearing can be obtained despite the slot in the rotor is challenged in this chapter.

The following literature review provides fundamentals for air pads understanding and mathematical tools to model the behaviour of air cushions. An introduction to the benefits brought by each step mentioned in this chapter is provided in the description of the methodology (6.2). Different mathematical approaches are proposed to model the load variation of an air pad over a slot in the rotor's bearing surface, based on the literature. An experimental setup aiming at challenging these models is presented and the subsequent measurement results are provided before the results are discussed and concluded.

6.1 Literature review

Basic knowledge about air pads was needed to understand how to use and optimise them for the SESHAT application. The literature was reviewed to answer the following questions:

- Are porous air pads suitable for high precision applications?
- How does an air pad with porous medium work?
- How can the load and stiffness of an air pad be modelled so that the load variation and stiffness reduction resulting from an opening in the bearing surface can be predicted?

The focus of this section will be the additional studies on the behaviour of air pads and particularly on porous media based air pads.

Air bearings have been used for a long time for high precision motions (Steger, 1965). Much information can be found about characterisation of air pads in the

literature: among them are how to optimise the design of air pads (Zhao et al., 2000), how to obtain the load capacity, stiffness or air consumption using different models depending on the characteristic of interest (O'Connor, n.d.).



Figure 6-1: NewWay air bearing advertisement ("Designing with Air Bearings," n.d.) showing air expelled from the entire surface of a concave airpad porous media under water

Uhlmann and Neumann (Uhlmann and Neumann, 2006) reported test results on different parameters to characterise an actuator spindle bearing based on a porous ceramic composite. Among the results, the pressure profile of an air cushion and a lift/load curve were presented as well as some stiffness measurement results. In this paper, they listed porous media air pads characteristics:

- high damping,
- silent operation,
- no wear,
- no heat problem,
- higher stiffness, load capacity and vibration stability than orifice based air pads,
- airflow lubrication leading to an absence of friction.

These characteristics make air bearings good candidates for high precision mechanics. However, they are linked to the conditions of use: stiffness and load capacity are increased by air gap reduction and pressure increase; load capacity is proportional to the air gap pressure with the porous surface area as the factor

of proportionality. Porous media air pads benefit from high damping capability and high tolerance to bearing surface damage thanks to the high number of micro-channels which controls the airflow across the entire bearing surface (in accordance with Figure 6-1).

Useful information concerning simulations and their comparison with measurements can be found (Uhlmann and Neumann, 2006):

- below an air pad, the flow characteristics lie in the crossing area between laminar and turbulent flow,
- the real material pressure distribution over the pad varies in comparison with the theory,
- there are concerns with reaching a constant pressure within the air gap, even if this latter is very reduced
- thermal environment has an impact on the quality of the bearing due to its impact on the air gap (dilatation of the air cushion, change in stiffness).

The information mentioned above (Uhlmann and Neumann, 2006) was later confirmed (Lim, 2009).

In 2013, Huang and his team (Huang et al., 2013) published an article focused on the influence of geometric parameters of flat porous aerostatic pads. Their work evaluated the porosity of the NewWay air pads' media at 0.17 by comparison with materials having different porosity. They observed that the load capacity is increased by a reduction of the porous media thickness. Nevertheless, they state that this increase in load capacity is limited by the decrease in stiffness, which is not quantitatively mentioned in the paper. A pressure distribution of the air cushion is given with respect to the distance from the centre of the pad. They reported that the load capacity of pads with 5 μm thick air gaps is negligibly affected by changes in speed whereas for larger air gap the load capacity is increased with accelerations and decreased with decelerations (Huang et al., 2013).

Another source of information is the guide delivered by NewWay (NewWay, 2006), aiming at providing its reader with basic knowledge and understanding of

the different parameters and how they affect the use of air pads. This guide gives one reduction of load capacity due to an opening in the bearing surface as an example, without any explanation on how it was computed.

6.2 Methodology

Within the global research approach presented in Figure 3-2, this chapter details the points 4 (actual solution design) and 5 (tests of the elements). As mentioned, part of the design of the actual solution (point 4) was to increase the size of the air pads in order to increase the stiffness. However, the stiffness does not result from the bearing area but from the pressure of the air cushion.

The air bearing is composed of

- a pad casing attached to a stator and receiving the air from an air pipe,
- a porous media attached to the pad casing and spreading the air over its surface (see Figure 6-1),
- an air cushion supplied by the porous media and losing air at its edges,
- a bearing surface (belonging to the rotor) pressing against the air cushion.

The air bearing assembly is characterised by

- an input air pressure with a nominal value provided by the manufacturer,
- a lift, or air gap (the thickness of the air cushion), the distance between the bearing surface and the air pad (see Figure 6-2),
- a stiffness k , which is a function of the lift for a given pad (following a curve like the one in Figure 6-11).

The question of whether the stiffness would be sufficient for the SESHAT led to the need to determine the load reduction due to the opening in the bearing surface (the stiffness is derived from a load and a displacement). The load of an air pad rigidly fixed to a stator results from the average pressure of the air cushion. As a result, in order to answer the initial question, the proposed mathematical models are focused on air cushions. These models were found in the literature where they described air cushions lying between a porous media and a surface without opening, thus losing air on the sides only. From this observation, the question of whether such models were applicable to an opening in the bearing

surface arose. As the lift is much tighter than the opening (Figure 6-2) while the pressure in the opening is much smaller than within the air cushion, the possibility of a Venturi effect (Dunărea, 2016) was considered, which led to a simulation of the air cushion (Figure 6-3).

A reduction of the average pressure of the air cushion is engendered by the slot sliding below the air pad. Two approaches were considered to model the pressure distributions of the air cushions leading to pressure reduction:

- the pressure distribution of the air cushion is considered applicable to all air pads and the maximum pressure is proportional to the bearing area,
- the pressure distribution features an edge effect with a width independent of the area, thus limiting the maximum pressure for small areas.

The question of whether a twist of the air pad had an influence on the load variation was also treated. The load variations resulting from these approaches were computed. The next step was the validation of the models. A test bench was designed in order to challenge the mathematical approaches proposed and select the better. The most significant sources of uncertainty were presented, among which the stiffness of the measurement setup and the sources influencing the repeatability were taken into account in the measurement results.

6.3 Mathematical models

No report could be found in the literature concerning the behaviour of an air cushion when it encounters an opening in the bearing surface as depicted in Figure 6-2. A suction, resulting from a Venturi effect (Dunărea, 2016), was suspected to exist at the edges of the slot in the bearing surface. Thus, a simulation aiming at comparing the air cushion pressure profile when it encounters an opening in the bearing surface with when it encounters an edge of the pad's porous media was performed.

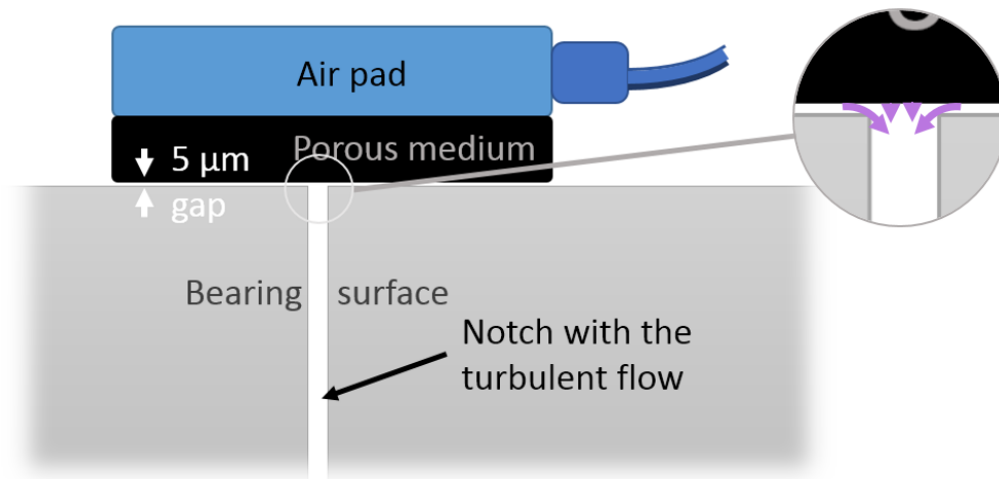


Figure 6-2: Schematic side view of the air pad.

The air is expelled by the porous media into the $5\ \mu\text{m}$ gap between the air pad and the bearing surface. During the passing of the slot, some air will be expelled into this channel in the bearing surface.

The software COMSOL Multiphysics 5.2 was used for this purpose: a turbulent flow expelled from the porous media with the supplier's nominal pressure was modelled and the pressure distribution after the air cushion stabilisation was observed. The simulation results depicted in Figure 6-3 show that no significant difference can be observed between the air behaviour under the porous media near an edge of the porous media or near an edge of the bearing surface. Thus the Venturi suction, if any, is negligible. As a result, these two types of edges could be similarly modelled in the following mathematical approach.

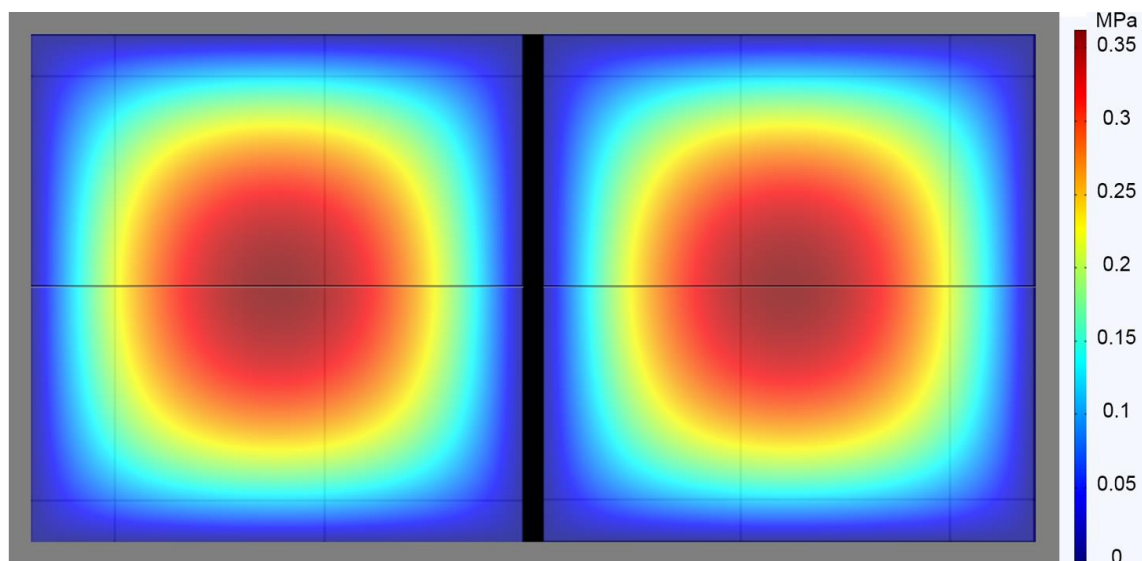


Figure 6-3: Simulation result on air pads showing the similar behaviour of the air under the porous media of the pad (pressure distribution in rainbow colours) whether it approaches the edge of the pad (grey line) or the edge of the bearing surface (black line)

The following computations model the load of the pad as it transverses the slot in the bearing surface. In order to perform this analysis, several assumptions were made:

- The system can be considered to be at equilibrium such that the simulation will be based on an instantaneous snapshot of the transition.
- The stiffness of the bearing surface, air pad casing and porous media are such that the deformations due to applied forces are negligibly small.
- The line of action of the force on the air pad is at the centre of the air pad's length.
- The slot is parallel to the air pad's edge, and any bevels or imperfections are neglected.
- The variation of atmospheric air pressure around the pads is negligible such that the relative air pressure on either side of the pads is zero.
- The dimensions of the air pads and slots are nominally correct such that the dimensional errors have a negligible influence.
- The friction between the pad and the spherical end screw prevents any twist.
- The effect of the bearing surface roughness is negligible such that the model is equally applicable to the entire bearing surface.

6.3.1 Model based on the nominal average pressures as a function of the area of the bearing surface

In this model, nominal average air pressures P_{Av} (in Pa) were computed, using NewWay data sheets, and expressed as a function of the nominal areas A_{Pad} (in m^2). The corresponding data points appear in blue in Figure 6-4. A best fitting equation (6-A) was defined for these points, it appears as the dotted yellow curve following a logarithmic shape in Figure 6-4.

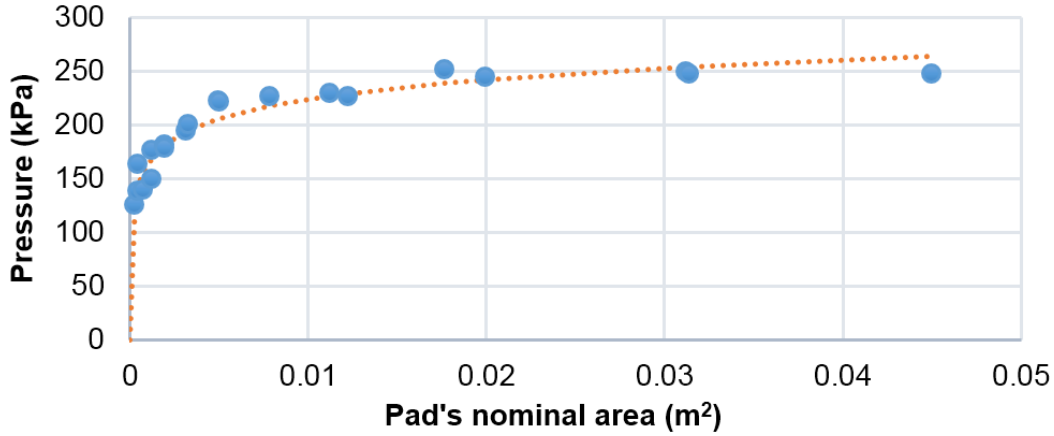


Figure 6-4: Pads' nominal average pressure as a function of the pad's area.
The best fit in orange corresponds to the following equation (6-A).

$$P_{Av} = \begin{cases} 26\,380 \cdot \ln(A_{Pad}) + 345\,792 & \text{for } A_{Pad} \in [2 \cdot 10^{-6}; 4.5 \cdot 10^{-2}] \\ 0 & \text{for } A_{Pad} < 2 \cdot 10^{-6} \end{cases} \quad (6-A)$$

Equation (6-A) defines the average air cushion pressure for pads of any area. The load F_{Pad} of the pad is obtained by multiplying the average pressure P_{Av} by the bearing area A_{Pad} :

$$F_{Pad} = A_{Pad} \cdot P_{Av}(A_{Pad}). \quad (6-B)$$

Equation (6-B) is equally applicable for a bearing surface reduced by a slot. In such case, the bearing surface can be redefined as shown in Figure 6-5 and the air pad considered as two contiguous pads with areas A_1 and A_2 as defined in equations (6-C) and (6-D) respectively.

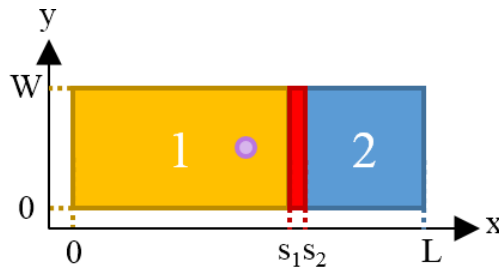


Figure 6-5: Air pad bearing surface shared by the slot in two parts identified as 1 and 2.
The pad has a length L and a width W ; the width of the red slot is s_2-s_1 ;
part 1 is to the left of the slot, in yellow; part two is to the right of the slot in blue;

$$A_1 = W \cdot s_1 \quad (6-C)$$

$$A_2 = W \cdot (L - s_2) \quad (6-D)$$

the spherical end screw loading the pad appears in the middle, in purple.

The force F_T resisted by the spherical end screw results from the addition of the forces F_{P1} and F_{P2} generated by each part:

$$F_T = F_{P_1} + F_{P_2}. \quad (6-E)$$

The mathematical model for the load variation results from the combination of the previous equations:

$$\Rightarrow F_T = W \cdot s_1 \cdot 26\,380 \cdot \ln(W \cdot s_1) + W \cdot (L - s_2) \cdot 26\,380 \cdot \ln(W \cdot (L - s_2)) + 691584. \quad (6-F)$$

6.3.2 Model based on a pressure variation related to an equation found in the literature

Based on the curves found in the literature concerning large air pads (O'Connor, n.d.), an approximation of the pressure $P(\alpha)$ as a function of the position α , the average pressure over a pad P_{Av} and the maximum distance d to the pad's centre could be given by the equation (6-G) below:

$$P(\alpha) = 1.1 \times P_{Av} (1 - (\alpha/d)^{10}) \quad (6-G)$$

This pressure distribution equation is defined for the dimensions of a pad with P_{Av} and d parametrized using the manufacturer's data. If there is a slot reducing the bearing surface to a length λ , then x replaces α and $P(x)$ equals $P(\alpha)$ from zero to the half of the length of the remaining bearing surface, then it follows the same curve reversed:

$$P(x) = \begin{cases} P(\alpha), & x \in [0, \lambda/2] \\ P(d - \lambda + \alpha), & x \in]\lambda/2, \lambda] \end{cases} \quad (6-H)$$

This resulting pressure distribution is comparable with the simulation results outlined in section 6.2, as shown in Figure 6-6, as well as those observed in previous studies (Rasnack et al., 1974). It should be noted that, despite the COMSOL simulation was performed on a 12 mm × 24 mm pad, its results are equally applicable to air pad of any size, including the 20 mm × 40 mm which are the main focus of this study.

The mathematical model was applied to an air pad with a length $d = 24$ mm and a maximum pressure without slot $P_{Av} = 38.8$ kPa. Due to the slot, the bearing surface was reduced to a dimension $\lambda = 12$ mm. Thus, the black curve in Figure 6-6 shows the curve of equation (6-H) for $\alpha \in [0, 6]$ – giving the pressure profile

of the air cushion from an edge ($\alpha=0$ mm) to the maximum reached in this configuration (when $\alpha = \lambda/2 = 6$ mm).

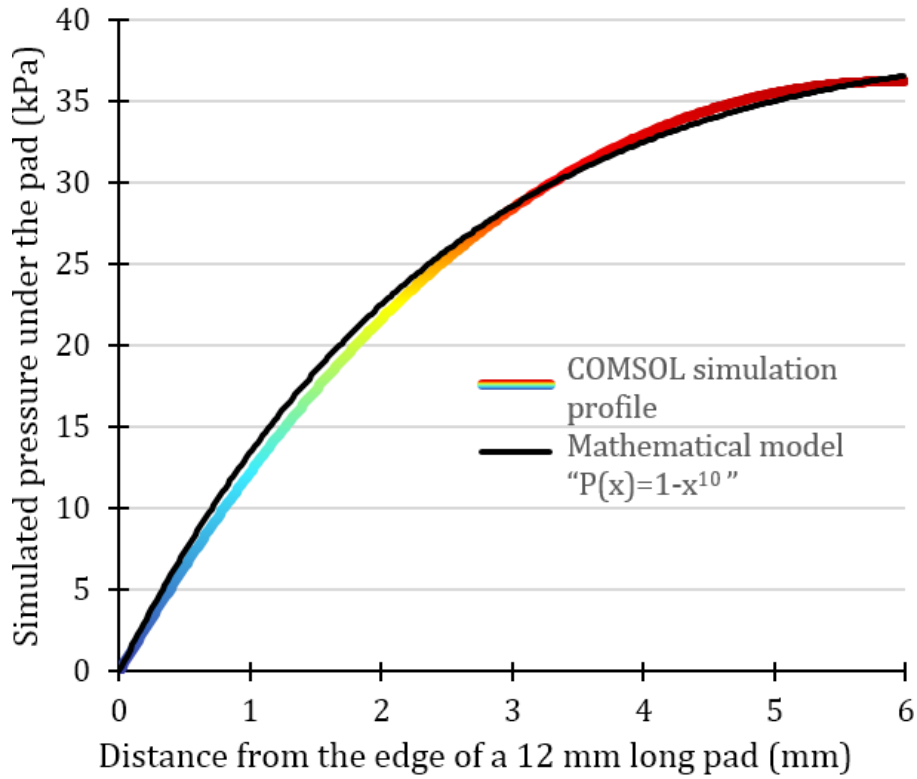


Figure 6-6: Comparison between the COMSOL simulation result and the proposed model, for a 12 mm long bearing surface under a 24 mm long air pad.

In this model, two halves of the pad are considered as two contiguous pads: one to the left of the spherical end screw (appearing in pink in Figure 6-7) and one to its right.

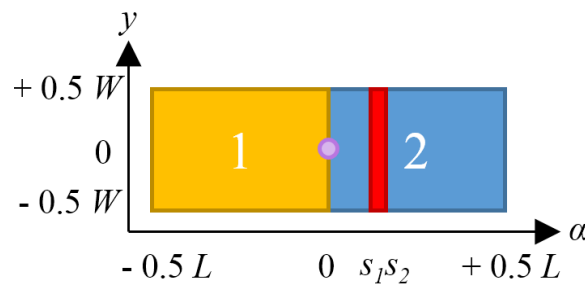


Figure 6-7: Top view of an air pad.

The bearing surface of width W and length L is shown separated into two halves (1 in yellow and 2 in blue). The red region represents the slot which has a thickness of s_2-s_1 . The position of the spherical end screw is shown in pink in the centre.

The pressure is shared over two distinct regions that are independent from the two half-pads aforementioned: P_I is to the left of the slot while P_{II} is to the right of the slot. P_I and P_{II} appear in Figure 6-8 as thick lines while their integrals, P_1 and

P_2 , factored in the following computations are coloured according to the half-pads 1 & 2. The variables x_I and x_{II} of the mathematical profile description are introduced in the same figure.

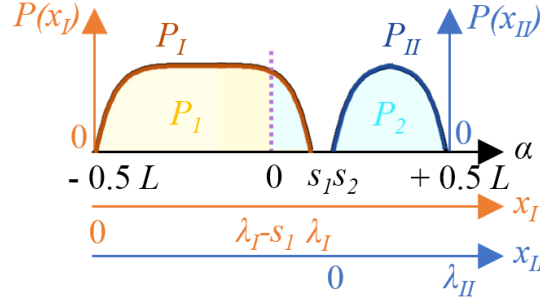


Figure 6-8: The pressure distributions appear as two thick curves: P_I and P_{II} are identified. The integral P_1 is shown in light yellow and P_2 in light blue, on each side of the pad's middle shown as a purple dashed line. The variables x_I and x_{II} are introduced.

The total load lift from the pad, F_T , is resisted by the spherical end screw and is equal to the sum of the forces generated by the two sides of the pad (F_{P_1} and F_{P_2}):

$$F_T = F_{P_1} + F_{P_2}. \quad (6-I)$$

For each side, the reaction force is equal to the integral of the 2D pressure distribution $P(x, y)$ over the cross sectional area (A) of the side. The influence of the pressure distribution in the z direction is approximated as a constant named k .

$$P(x, y) = k \cdot P(x), \quad (6-J)$$

$$F_P = \int \int_A P(x, y) \cdot dA. \quad (6-K)$$

Substituting values for the limits in the coordinates x and y shown in Figure 6-7 gives the following expressions for the forces of the two sides as a function of the slot position s :

$$F_{P_1}(s) = \int_0^{\lambda_1 - s_1} \int_{-0.5W}^{0.5W} P_I(x_I, y) \cdot dy \cdot dx_I, \quad (6-L)$$

$$F_{P_2}(s) = \int_{\lambda_1 - s_1}^{s_1} \int_{-0.5W}^{0.5W} P_I(x_I, y) \cdot dy \cdot dx_I + \int_0^{\lambda_2} \int_{-0.5W}^{0.5W} P_{II}(x_{II}, y) \cdot dy \cdot dx_{II}. \quad (6-M)$$

A factor K can be used as an approximation for the integral along y :

$$K = k \cdot W. \quad (6-N)$$

The force can then be computed using the following expressions which were implemented within a MATLAB function:

$$F_1(s) = K \int_0^{\lambda_1 - s_1} P_I(x_I) \cdot dx_I, \quad (6-O)$$

$$F_2(s) = K \left(\int_{\lambda_1 - s_1}^{\lambda_1} P_I(x_I) \cdot dx_I + \int_0^{\lambda_2} P_{II}(x_{II}) \cdot dx_{II} \right). \quad (6-P)$$

6.3.3 Model with a twist

In this model, there is no friction between the spherical end screw and the air pad casing. When the term *twist* is employed, it is such that the twisted air pad is at equilibrium. The stiffness of the pad's surface is a function of the lift (see Figure 6-11), thus of the displacement. When the slot is deforming the air cushion on one side of the pad, the stiffness of this side is decreased. Nevertheless, the stiffness stays a function of the lift. As a result, the overall stiffness of the twisted pad results from an equilibrium between the lift reduction increasing the stiffness of the half pad with the slot and the lift increase decreasing the stiffness of the half pad without slot. This could be modelled using non-linear spring constants for each half pad. However, the aim of this study is to know the stiffness variation (and thus the load variation) of the air pad. The stiffness distribution over the half pads does not add relevant information to this study. When the pad is twisted, the force generated by the half pad with the slot is equal to the force generated by the half pad without the slot. As a result, the sum of the forces of the twisted air pad will equal the sum of the forces of the non-twisted air pad modelled in the previous paragraphs. The air pad will twist but it will not influence the results of the force or stiffness generated by its overall surface.

6.4 Experimental setup for model validation

In order to validate the model, experimental tests were performed. A 20 mm × 40 mm air pad was arranged to slide in a direction perpendicular to a lapped part which contained a 1.5 mm wide slot. During this process the load generated by the pad was measured.

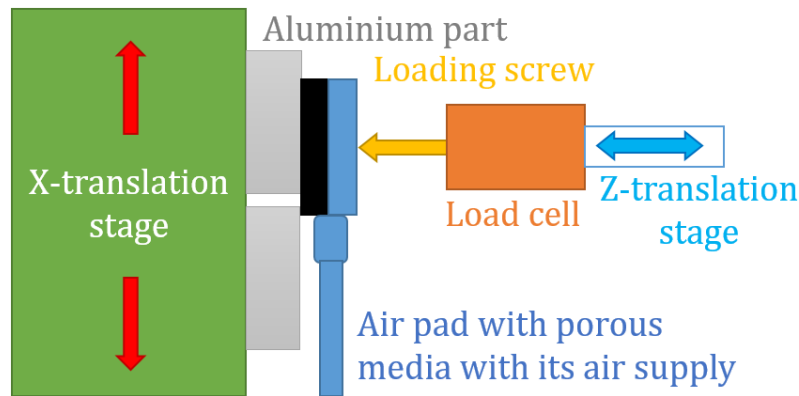


Figure 6-9: Schematic of the test bench principle (top view)

The test bench (see Figure 6-9 & Figure 6-10) was composed of different elements:

- The 20 mm × 40 mm air pad being tested with a temperature controlled (to ± 0.5 °C) air input.
- An aluminium plate featuring a 4 mm deep and 1.5 mm large slot. The two sides were aligned to be parallel, and were obtained using lapping to produce a surface with a flatness of 2 μm and a roughness R_a of 0.4 μm ($\lambda_c=0.8$ mm, applying (ISO, 1996b)).
- A Moore Nanotech 350 UPL turning machine which was used for both pre-alignment and load control.
- A Maywoods Instruments U4000 load cell powered by a BST PSA30/3B power supply and read by a Keithley 175 multimeter. The resolution of this setup was 10 μV over a range of 4 mV. Calibration was performed across the expected loading range (0 to 11.5 kg) using a set of known masses prior to the experiment.

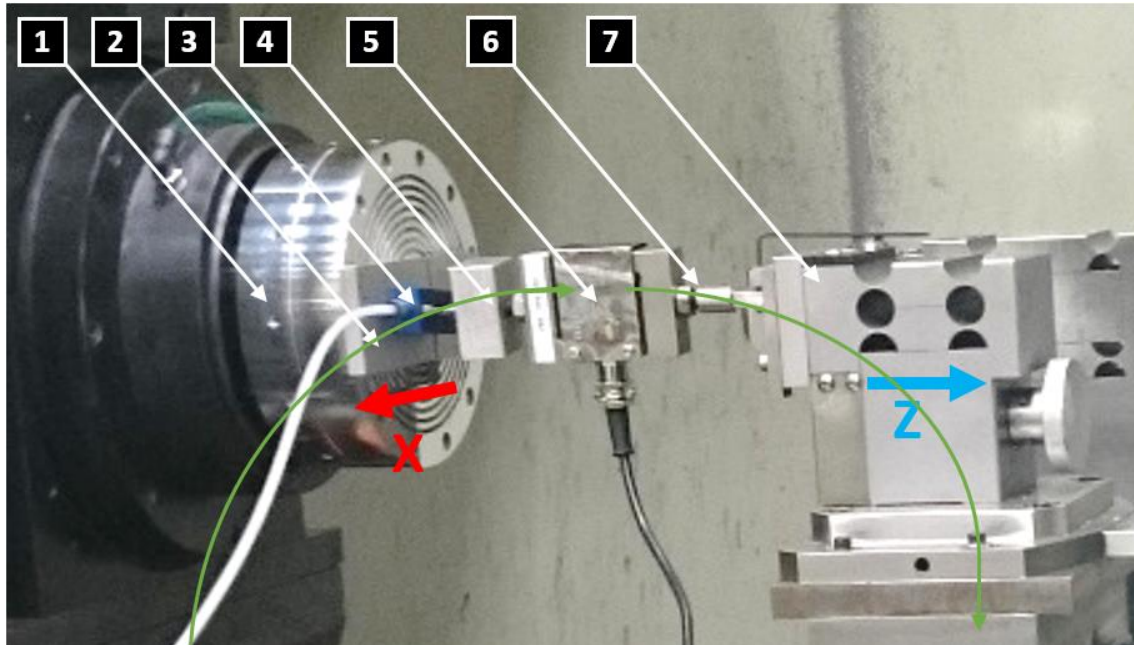


Figure 6-10: Overview of the test bench showing key components.

(1) The X translation stage of the turning machine (perpendicular to Z, toward the camera that shot the photo). (2) An aluminium plate containing the 1.5 mm slot which was held onto the translation stage by vacuum. (3) The air pad under test. (4) Adapter between the load cell and air pad loading spherical end screw. (5) The load cell. (6) A screw tightening the load cell and fitting with the machine's holding system. (7) The Z translation stage of the turning machine. In green, the metrology loop is represented, the part out of the image being within the Moore machine.

The two principal movements used in this experiment are the lathe's X and Z linear axes: the Z axis can be used to change the load applied by the air pad, and the X axis can be used to change the relative position of the slot with respect to the air bearing pad. The high stiffness of the precision turning machine minimises the errors of the measurement. The vacuum holder was used to secure the aluminium plate during the experiment.

6.5 Uncertainty contributors

The uncertainty on the load measurement obtained with the setup previously introduced results from the following contributions, themselves resulting from the following sub-contributions:

1. Environment
 - 1.1. Temperature
 - 1.2. Humidity
 - 1.3. Dust
 - 1.4. Vibrations

- 1.5. Convection
- 2. User
 - 2.1. Experience
 - 2.2. Time dedicated to setup optimisation
 - 2.3. Method
 - 2.3.1. Calibration process
 - 2.3.2. Sampling frequency
 - 2.3.3. Number of repetitions
 - 2.3.4. Choice of the position on the bearing surface
 - 2.3.5. Duration of measurement acquisition
- 3. Test bench
 - 3.1. Design
 - 3.1.1. Choice of the elements
 - 3.1.1.1. Stiffness of the metrology loop
 - 3.1.1.2. Thermal behaviour
 - 3.1.1.3. Heat generation
 - 3.1.1.4. Bearing surfaces form tolerances
 - 3.1.1.5. Linearity of the load cell
 - 3.1.1.6. Positioning resolution and stability
 - 3.1.2. Air pipes tightening
 - 3.1.3. Possibilities of alignment
 - 3.1.4. Bonding between the elements
 - 3.2. Cooling effect of the air decompression
 - 3.3. Calibration of the load cell
 - 3.4. Air gap evaluation
 - 3.5. Input air characteristics
 - 3.5.1. Temperature
 - 3.5.2. Pressure
 - 3.5.3. Cleanness
- 4. Data post processing
 - 4.1. Motion bias compensation (linear adjustment)
 - 4.2. Approximations

Special precautions implemented to reduce these contributions are mentioned throughout this chapter, nevertheless the influence of the design stiffness is discussed here, as it is the largest contribution to the error in the results. In the aforementioned setup, the load measured by the load cell will not be equal to the load variation undergone by the air pad, due to the limited stiffness of the setup.

The acquisition loop is composed of the n elements interacting with the measurement: the Moore machine, the screws and adapters, the load cell and the air pad, with their respective stiffness. The metrological loop (Figure 6-10) is characterised by the stiffness k_{total} such that:

$$k_{total} = \left(\sum_{i=1}^n \frac{1}{k_i} \right)^{-1} = \left(\frac{1}{k_{AirPad}} + \frac{1}{k_{Moore}} + \frac{1}{k_{LoadCell}} + \frac{1}{k_{Screws}} \right)^{-1}. \quad (6-Q)$$

For the computation sake, the acquisition loop is divided into two parts: one with a stiffness k_{AirPad} whose variation is to be determined and one with a constant stiffness k_{Setup} , as follows:

$$k_{total} = \left(\frac{1}{k_{AirPad}} + \frac{1}{k_{Setup}} \right)^{-1}, \quad (6-R)$$

$$\text{with } k_{Setup} = \left(\frac{1}{k_{Moore}} + \frac{1}{k_{LoadCell}} + \frac{1}{k_{Screws}} \right)^{-1}.$$

The force resisted by the pad is defined as the pad's stiffness times Δz , the distance to its resting position:

$$F = k_{total} \cdot \Delta z. \quad (6-S)$$

The resting position is an unknown, as well as Δz . To preload the air pad, Δz increases while z decreases during the machine's translation. When the air pad is preloaded, the machine does not move any longer in the z direction, then z is considered constant and therefore Δz as well (which is true to the parallelism error and the translation uncertainty in the x -direction). As a result, the load is proportional to the stiffness.

When the slot arrives under the air pad, the stiffness k_{AirPad} decreases by a factor γ_{Slot} to $k_{AirPadSlot}$, and thus the spring stiffness k_{total} decreases to $k_{totalSlot}$ such that

$$k_{totalSlot} = \left(\frac{1}{k_{AirPadSlot}} + \frac{1}{k_{Setup}} \right)^{-1} = \left(\frac{1}{\gamma_{Slot} \cdot k_{AirPad}} + \frac{1}{k_{Setup}} \right)^{-1}. \quad (6-T)$$

If we consider the nominal value for the air pad stiffness, an approximated setup stiffness computed from the stiffness of the Moore machine and the load cell (we consider the screws infinitely stiff) and a decrease of 15 % due to the slot, the theoretical result is

$$k_{Setup} = \left(\frac{1}{k_{Moore}} + \frac{1}{k_{LoadCell}} + \frac{1}{k_{Screws}} \right)^{-1} = \left(\frac{1}{50} + \frac{1}{7} + 0 \right)^{-1} = 6.1 \text{ N}/\mu\text{m}, \quad (6-U)$$

$$k_{total} = \left(\frac{1}{k_{AirPad}} + \frac{1}{k_{Setup}} \right)^{-1} = \left(\frac{1}{14} + \frac{1}{6.1} \right)^{-1} = 4.3 \text{ N}/\mu\text{m}, \quad (6-V)$$

$$\begin{aligned} k_{totalSlot} &= \left(\frac{1}{\gamma_{Slot} \cdot k_{AirPad}} + \frac{1}{k_{Setup}} \right)^{-1} \\ &= \left(\frac{1}{0.85 \times 14} + \frac{1}{6.1} \right)^{-1} = 4.1 \text{ N}/\mu\text{m}. \end{aligned} \quad (6-W)$$

As a result, a decrease $\gamma_{Slot} = 15 \%$ of the air pad stiffness generates a decrease of

$$\frac{k_{total} - k_{totalSlot}}{k_{total}} \times 100 = \frac{4.3 - 4.1}{4.3} \times 100 = 5 \% \quad (6-X)$$

on the stiffness measurement result, thus on the load measurement.

As a result, a correction factor ε must be applied to the mathematical model to compensate for the measurement setup imperfections and determine the final load F_F . It is applied to percentages as follows in equation (6-Y)

$$F_F = 100 - \varepsilon \cdot (100 - F_T) \quad (6-Y)$$

During the measurement, the setup stiffness is assumed infinite, the load variation measured is thus assumed to result entirely from the air pad stiffness variation. Consequently, ε has a value of

$$\varepsilon = \frac{100 - F_F}{100 - F_T} = \frac{100 - 95}{100 - 85} = 0.33. \quad (6-Z)$$

In other terms, the results are corrected by a factor κ such that

$$\kappa = \frac{F_F - F_T}{F_T} = \frac{95 - 85}{85} = 12 \%. \quad (6-AA)$$

6.6 Results

Evaluation of the test setup was performed by reproducing the load/lift curve and stiffness curves for the air pad of interest. These curves are provided by the manufacturer (NewWay, 2006) for larger air pads, however only one nominal data point had been given for the small air pads used in the SESHAT. In order to populate these curves, the load applied by the pad was incrementally adjusted from 22 N to 169 N (1 mV to 4.5 mV) in 16.3 N steps (0.5 mV). Each air gap was evaluated following several steps:

1. a given force F was applied to the air pad without air from the air supply,
2. the readout of the Z-axis was recorded,
3. the air supply was switched on,
4. the machine was translated along its Z-axis until the same force F was applied to the air pad,
5. the readout of the Z-axis was recorded again,
6. the change in the Z axis readout was used to approximate the air gap induced by the pad.

The measurement was performed between one and four times for a given load, as show in Figure 6-11.

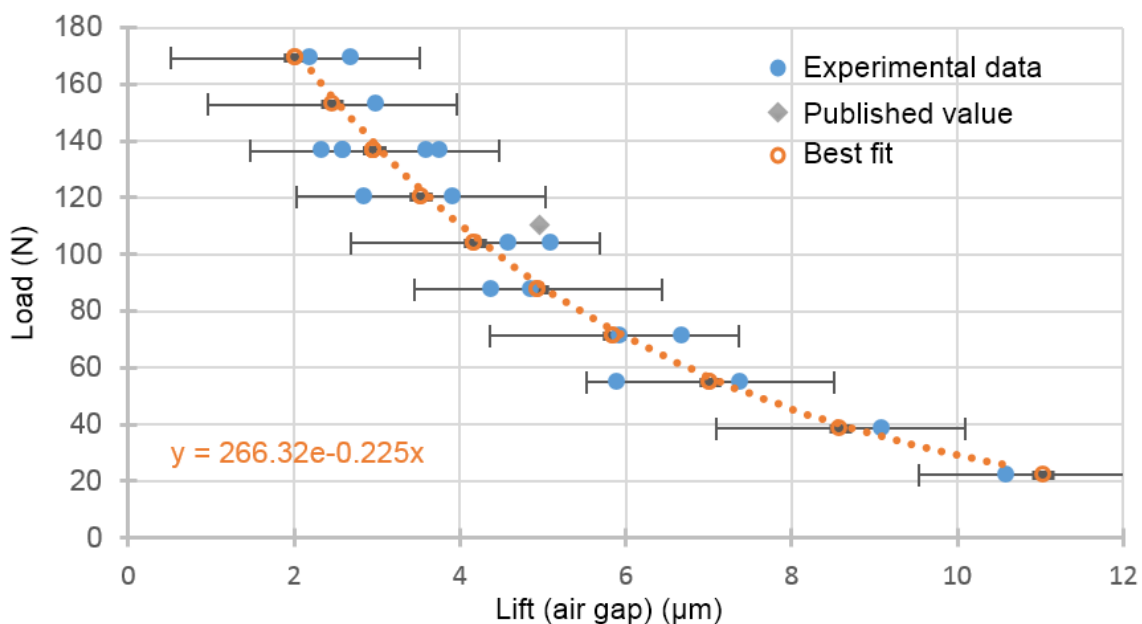


Figure 6-11: Lift/Load curve obtained with the 20 mm x 40 mm porous air bearing. The error bars demonstrate the uncertainty of each of the best fit values, which have 99.7% confidence intervals of ± 1 N and ± 1.7 μm , for the load and air gap, respectively.

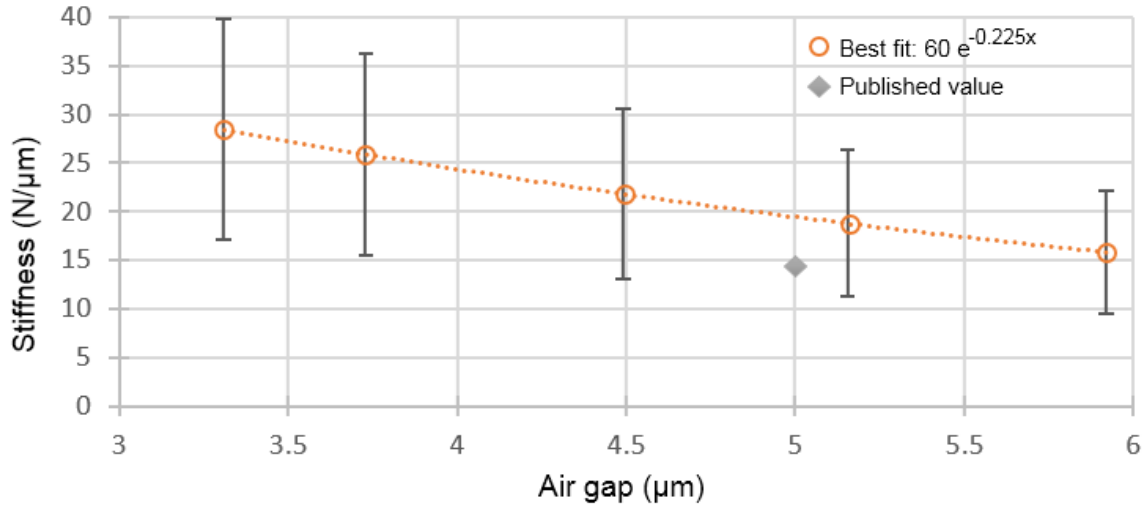


Figure 6-12: Stiffness as a function of the air gap for a 20 mm×40 mm porous air pad.

The error bars are derived from those obtained in the lift/load curve.

As expressed in equation (6-S), the force is related to the stiffness by a change in the distance between a theoretical equilibrium position and an actual position. This is expressed in this case study as a variation in the air gap. Thus, in order to obtain stiffness estimates s , the change in force was divided by the change in the air gap distance, both obtained from the load/lift curve:

$$s(a_n) = \frac{F(a_{n+1}) - F(a_n)}{a_{n+1} - a_n}, \quad (6-BB)$$

where a_n is the lift at a specific position n and a_{n+1} is the subsequent lift estimate. Both the stiffness s and the force F are deemed to be functions of the air gap thickness.

Force variation testing was performed by moving the slot from one end of the air bearing pad to the other end in 1 mm steps. At each position, the force measured by the load cell was logged. This measurement was repeated 6 times, with two nominally identical air pads. The two air pads data can be observed in Figure 6-13:

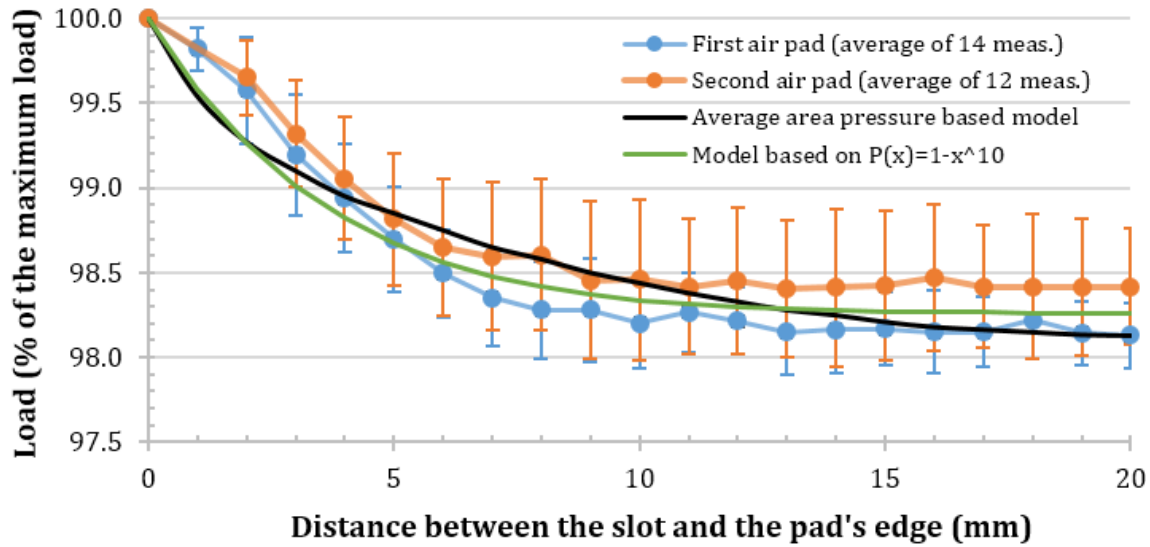


Figure 6-13: Load of a 20 mm× 40 mm air pad as a function of the position of a 1.5 mm large slot sliding below the pad, along its length. The results are expressed as percentages of the maximum load and the errors bars show the 67% confidence intervals.

The porous graphite air bearing pad surface was inspected after the experimental tests and shown not to be damaged. The average area pressure based model was adjusted to the measurement data using $\varepsilon_{AAPBM}=0.11$ (see equation (6-Y)), resulting in a correction factor $K_{AAPBM}=16\%$ (see equation (6-AA)), while the model based on the equation $1-x^{10}$ was adjusted to the measurement data using $\varepsilon_{EBM}=0.14$, resulting in a correction factor $K_{EBM}=12\%$.

The tests were performed in a temperature controlled room with a nominal at $20\text{ }^{\circ}\text{C} \pm 0.5\text{ }^{\circ}\text{C}$. Nevertheless, a load variation of 1% was seen in the repeatability measurements, which was most likely associated with thermal effects. Indeed, the air pads casing supporting the loading point is in aluminium and the air decompression has a cooling effect. To minimise this effect, the measurements were performed as fast as possible.

6.7 Conclusion and discussion

Models of the load reduction on an air pad while passing a linear opening have been presented and experimentally validated. According to the results, the model based upon the expression of the air cushion pressure is more appropriate than the model based upon the expression of the average value for an air pad of a given surface. The pressure distributions and integration presented have

potential for use in a broad range of air pad designs, however, adjustment based on measurements is still necessary to make use of this approach.

The lift/load and stiffness curves for NewWay 20 mm × 40 mm air pad with porous media is provided. As stated in their manufacturer's datasheet (NewWay, 2006), these air pads can be reliably used above an opening without being damaged.

Concerning the SESHAT design project, the provided model shows that the load variation is not larger than 16 %. This means that the actual stiffness remains above the required 50 N/μm at all times.

6.7.1 Imperfections in test bench setup

In this chapter, new analytical models are presented to simulate the response of porous media air pads when the bearing surface contains a slot. Comparison of its results with experimental data has demonstrated this model captures well the behaviour of the pad. However, despite the quality of the correlation, individual data points were found to be noisy in the experimental data set. This noise was associated with the test bench setup. A number of enhancements for future testing include:

- A loading spherical end screw could be machined in order to make direct contact with the load cell, thereby reducing the number of interfaces and increasing the mechanical stiffness of the measurement system.
- An automated voltage measurement routine should be implemented. This should decrease the measurement uncertainty by facilitating faster measurement protocols, thus reducing thermal influences and enabling dynamic measurements to be performed.
- An independent displacement sensor should be inserted in the setup to directly measure the air gap rather than relying on the displacement recorded by the diamond turning machines motions. This would reduce the uncertainty associated with lift/load data acquisitions, consequently with the lift/stiffness data.

- The resolution of the load cell (currently 0.4 N), should be improved to enhance the results.

6.7.2 Correction factor needed to have the model fitting the data

The model provided considers the air gap as a constant. In fact, as it slides above the opening, the stiffness of the pad is reduced. This engenders a decrease of the air gap that leads to an increase in the stiffness and load capacity (following a curve similar to the lift/load curve), thus reducing the impact of the slot on the load capacity.

An additional limitation is the measurement system which has its own stiffness reducing the measured load variation. As mentioned in the previous discussion section, increasing the stiffness would improve the measurement setup. Additionally, it can be stated that knowing the overall stiffness of the measurement acquisition with low uncertainty would allow for a more accurate compensation using the equations provided in section 6.5.

6.7.3 Further work

Further simulations should be performed, based on the models presented in this chapter, in order to determine the impact of the stiffness variation due to the slot on the measurement uncertainty of the SESHAT's acquisitions.

Additionally, further research on how the stiffness of an air pad is affected by an opening could lead to a calibrated theoretical model. This would lead to a generalisation of this model, which would predict load variation for any type of air pads and any type of opening in the bearing surface.

CHAPTER 7 MANUFACTURE AND MACHINING OF THE ROTOR BUILT BY SELECTIVE LASER MELTING (SLM) TO A MICROMETRIC FORM DEVIATION

The conclusion of section 5.4 is that the most appropriate material for the rotor is a titanium alloy and that, to reduce the mass of the part, an additive manufacturing route should be considered. This chapter presents such manufacturing alternative that uses selective laser melting (SLM) to produce a lightweight near shape rotor followed by a mechanical finishing process that targets its final 2 μm form deviation requirement.

7.1 Literature review of additive manufacturing techniques and machining of Ti-6Al-4V



Figure 7-1: EBM machine, courtesy of Arcam EBM, vs SLM machine, courtesy of SLM solution

Selective Laser Melting (SLM) and Electron Beam Melting (EBM) are two additive processes reported to produce Ti-6Al-4V parts (Rafi et al., 2013), which require large machines, as appear in Figure 7-1. These machines are composed of a powder receptacle, whose size limits the maximum size of the AM part to be manufactured. There is a powder container linked to a moving bridge spreading the powder in the machine, which can be observed by a camera (see Figure 7-2). A high power laser is controlled by a command unit.

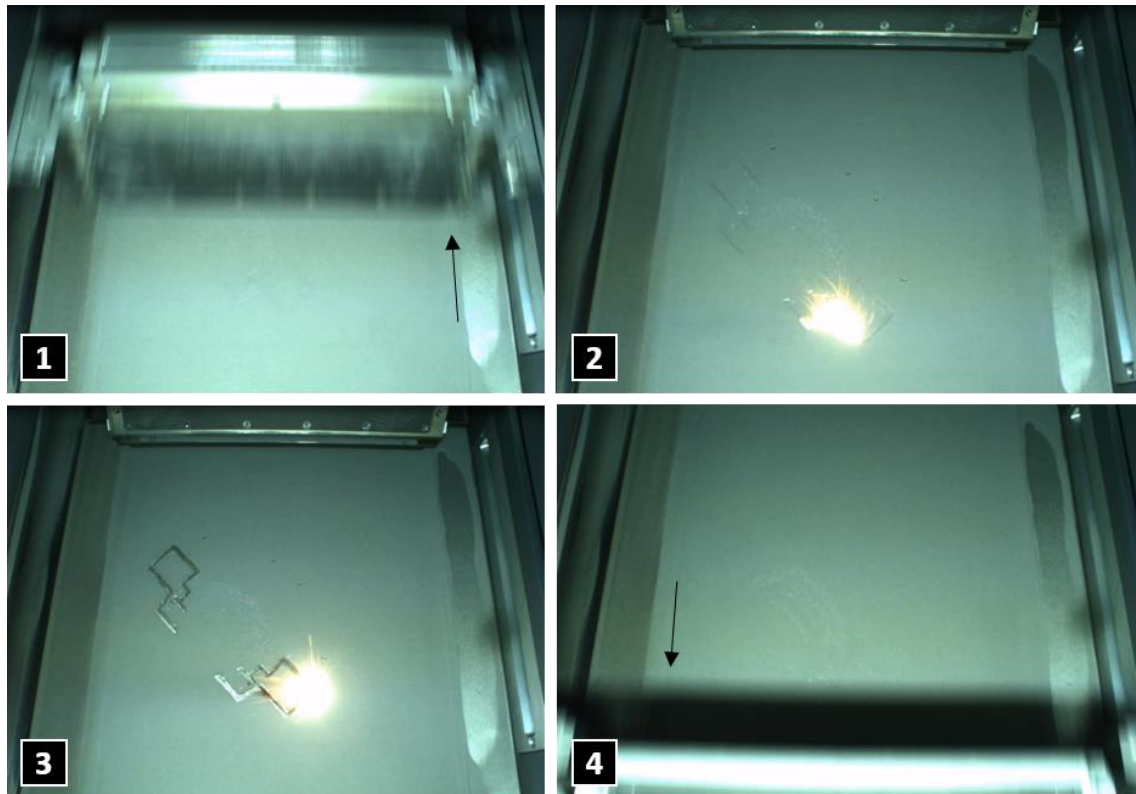


Figure 7-2: Inside the SLM-Solution machine, during the rotor manufacture

- 1) The recoater deposits a layer of Ti6Al4V powder on the previously fused part
- 2) The laser exposes the contours of this layer
- 3) The laser exposes the volume of the layer
- 4) The build platform lowers by one layer thickness and the recoater deposits a new layer before the process repeats.

In both SLM and EBM techniques, the metallic powder bed is pre-heated and then melted. The pre-heating reduces the thermal stresses by reducing the thermal gradient between the powder and the part (Rafi et al., 2013). However, the material structure differs with the manufacturing process. The roughness obtained by SLM is lower than the roughness obtained by EBM, while the ultimate tensile strength is higher for SLM than for EBM. EBM produces samples with a higher ductility while SLM produces samples with a higher tensile strength and resistance to fatigue (Rafi et al., 2013). The differences highlighted in Rafi's work are not helpful to determine whether EBM or SLM is better for the SESHAT application, as the two techniques enable the manufacturing of a non-porous titanium part with the shape designed for the rotor. In the end, SLM was selected to produce the rotor due to its lower production cost.

Shape Adaptive Grinding has been used to finish AM parts. Shape Adaptive Grinding is based on abrasive pellets positioned at the surface of an elastomer,

which allows for free-form finishing (Beaucamp et al., 2015). Beaucamp demonstrated that Shape Adaptive Grinding can reduce the Ra roughness of a Ti-6Al-4V part manufactured by EBM from 7.8 μm to 18 nm. Such a low Ra value meets the design requirements of the SESHAT's rotor.

Grinding and turning have also been successful in machining Ti-6Al-4V parts (Bordin et al., 2017). However, only turning, under carefully chosen conditions, can achieve SESHAT's form and roughness tolerances. (Bordin et al., 2017).

Residual stresses induced during additive manufacturing is higher along the laser path direction (Mishurova et al., 2017; Yadroitsev and Yadroitsava, 2015), thus, the build orientation of the rotor should be carefully considered. The residual stress produced by the thermal gradients during AM disappear after a heat treatment (Mishurova et al., 2017). However, the amount of stress imparted during machining process can vary significantly (Brinksmeier et al., 1982), and it is predicted to affect the final shape of the rotor after cutting the radial wire access notch.

7.2 Additive manufacturing

A technical drawing for a metallic rotor was produced based on the design requirements of the SESHAT (see annex 5.4). In order to facilitate effective SLM, an external wall was left open to enable powder removal at the end of the process. During manufacturing, a rotor without the holes nor notch was produced. The walls were designed to be thicker to allow for later machining, including threading and cutting.

For components showing no bulk distortion, 0.5 mm additional thickness is sufficient to enable effective material removal through traditional machining. To minimise the thermal stress effects, the rotors were manufactured at a build angle of 6° between the support and the part (see the increasing support length number 1 in Figure 7-3). This small build angle required the production of supports within the sample, shown in Figure 7-3, number 3.

The orientation of the notch was set perpendicular to the laser path (see the wall behind number 4 in Figure 7-3), which improved the symmetry with the notch

plane. Two rotors were manufactured following this description, namely version 1 and version 2.

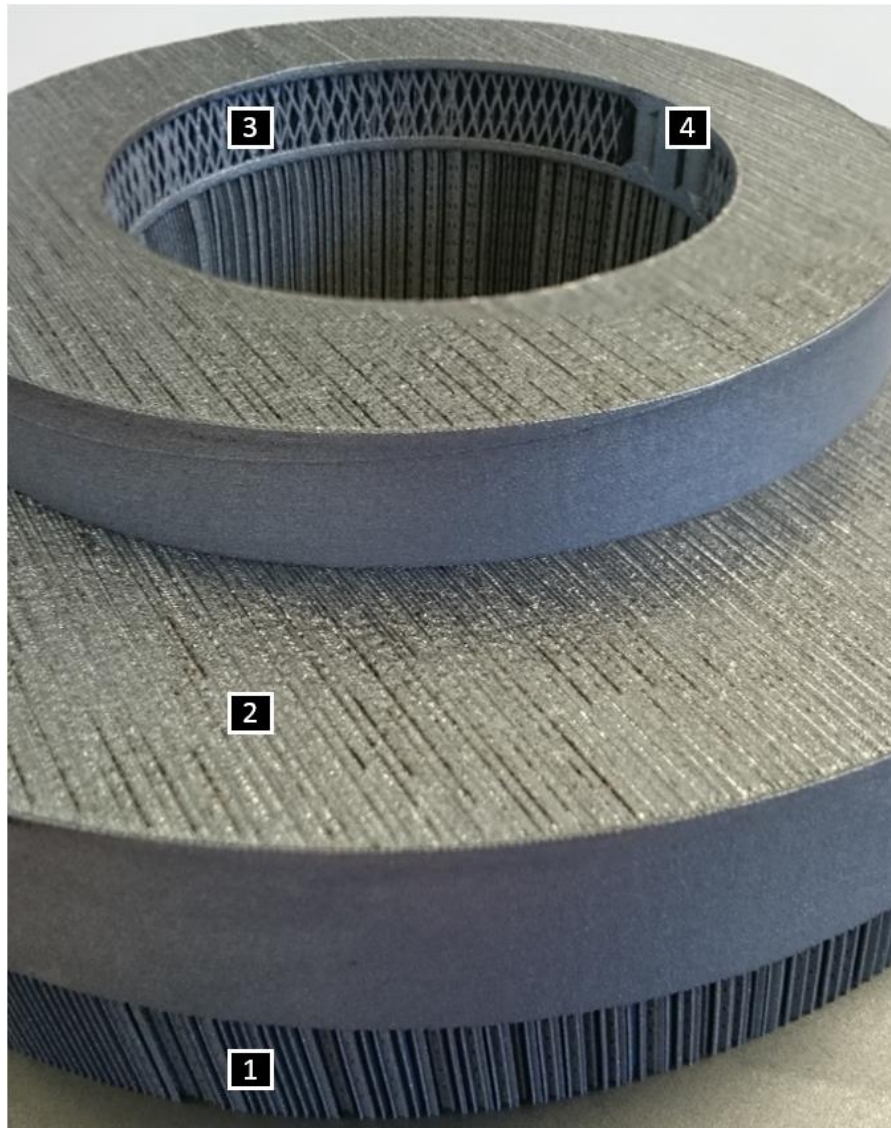


Figure 7-3: TiAl6V4 rotor version 1 after Selective Laser Melting.

The structures required to support the bottom surface of the rotor are shown (1). The surface pattern reflects the staircase effect associated with the low inclination surface of SLM (2). The internal structures of the rotor is an array of rhombuses (3). At the location of holes and the rotor notch, the part is solid (4).

The rotors were manufactured using a machine called SLM 280HL, produced by SLM Solutions, which is depicted in Figure 7-4 below. This system features a 400 W ytterbium continuous wave fibre laser operating at a wavelength of 1070 nm and a 3 axis scanning system. The layer thickness was 50 μm and the platform temperature was 200 $^{\circ}\text{C}$.

The rotors were heat treated at 650 °C for two hours in a vacuum furnace with a subsequent cooling under vacuum to 100 °C. Below this temperature, the parts were air-cooled. Heat treatment was performed before removing the supports to the titanium base plate on which the samples were manufactured. The first version of the rotor after SLM appears in Figure 7-3 above.



Figure 7-4: The SLM 280 HL machine with the operator during powder removal of the SESHAT's rotor

The first version of the rotor was found to be elliptical. The semi-minor axis, which corresponds to the built direction and perpendicular to the laser path, was 1.2 mm smaller than the nominal rotor dimension. Unfortunately, the 0.5 mm additional thickness was not enough to compensate for such error. For this reason, the rotor version 1 was used to optimise the machining parameters and to identify the most suitable finishing process. For the second version of the rotor, the oversizing of the external walls was extended to 2 mm. This extension increased the amount of deposited material and thus the residual stresses due to extra machining.

After manufacturing version 2 of the rotor, cracks were observed in the support structure. Nevertheless, this was found to have a minimal impact on the global orientation of the sample and the relative build direction. The rotor version 2 is

shown in Figure 7-5. The second version of the rotor had similar magnitude elliptical distortions as the rotor version 1 but with added material to allow the rotor version 2 to be machined to the correct dimensions (see Figure 7-6).

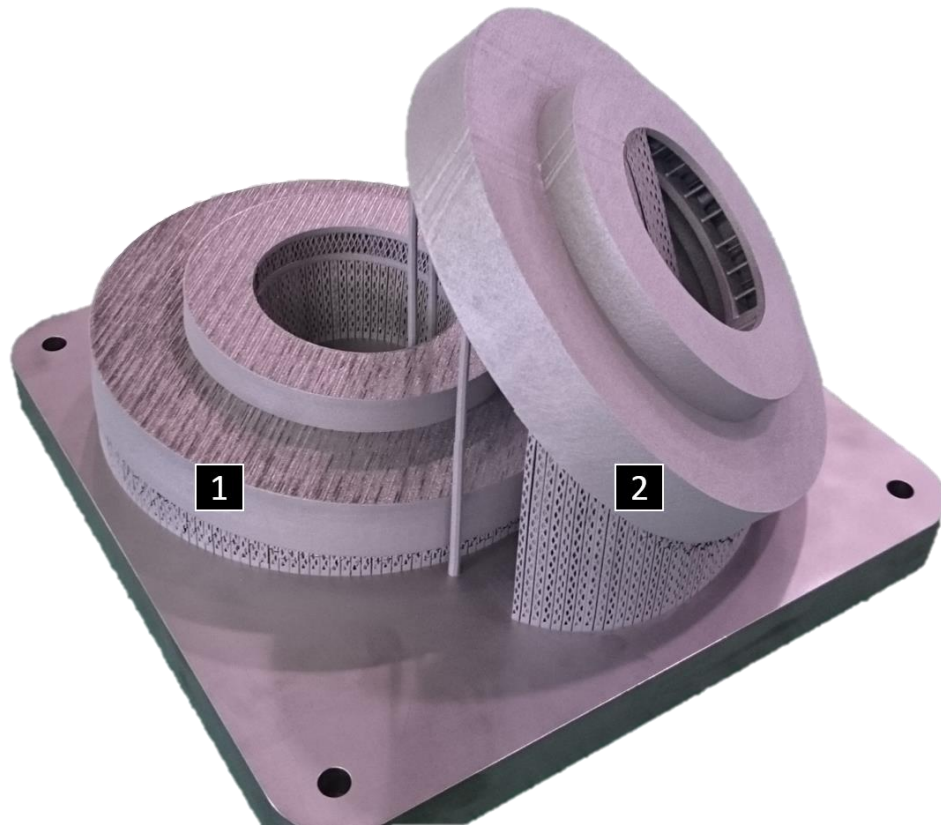


Figure 7-5: Rotor version 2 (1) was printed simultaneously with a spare part (2) in order to save handling time.

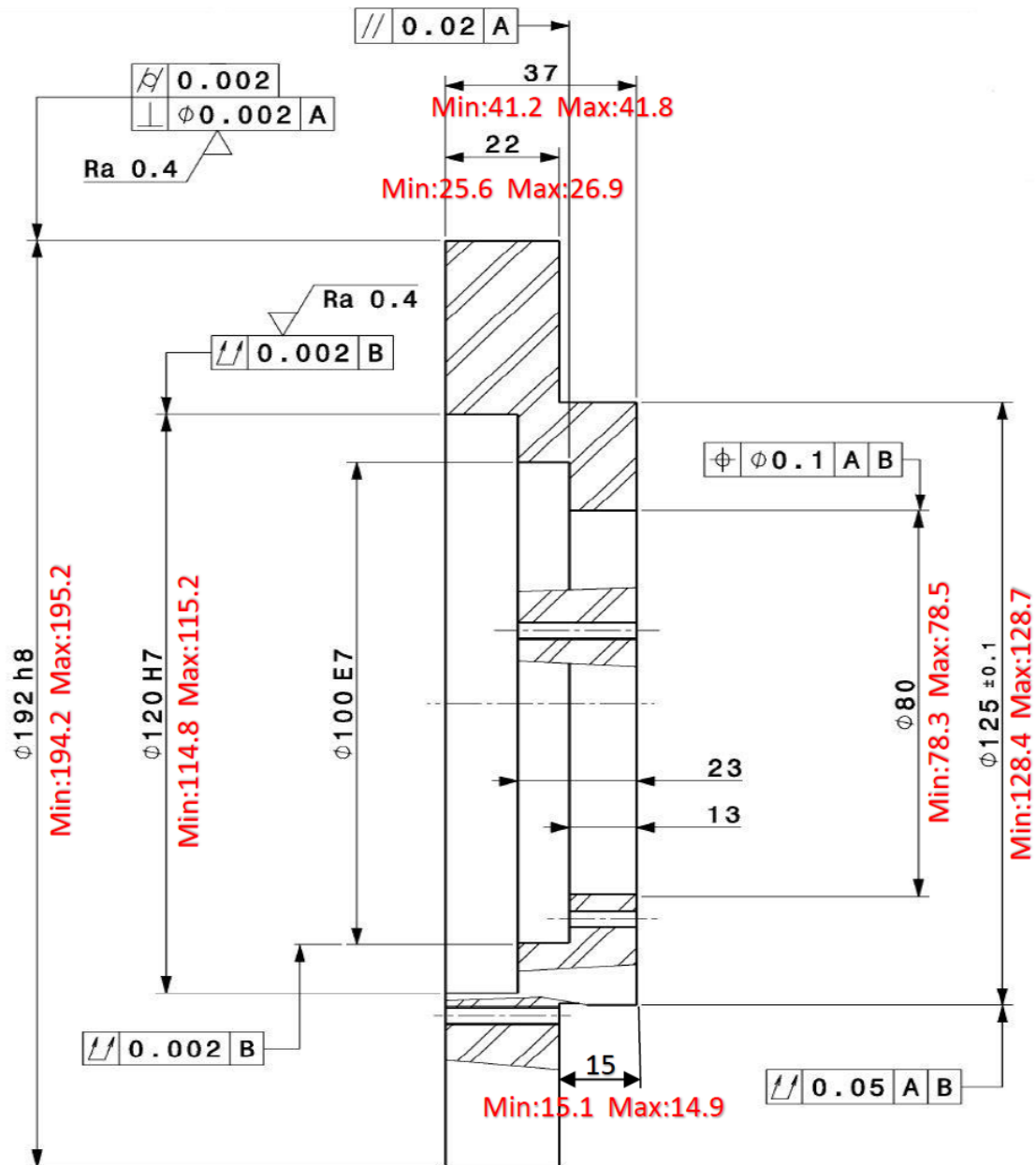


Figure 7-6: Results from the metrology applied to the rotor version 2 despite the large distortions, the rotor can be machined.

7.3 Machining of the part

The aim of the machining trials was to determine whether the tolerance on the form for the SESHAT could be reached on a part obtained by additive manufacturing. Two types of water coolant based machining were compared: turning and grinding. These traditional techniques of machining are known to achieve excellent form results on parts featuring a rotational axis.

7.3.1 Grinding

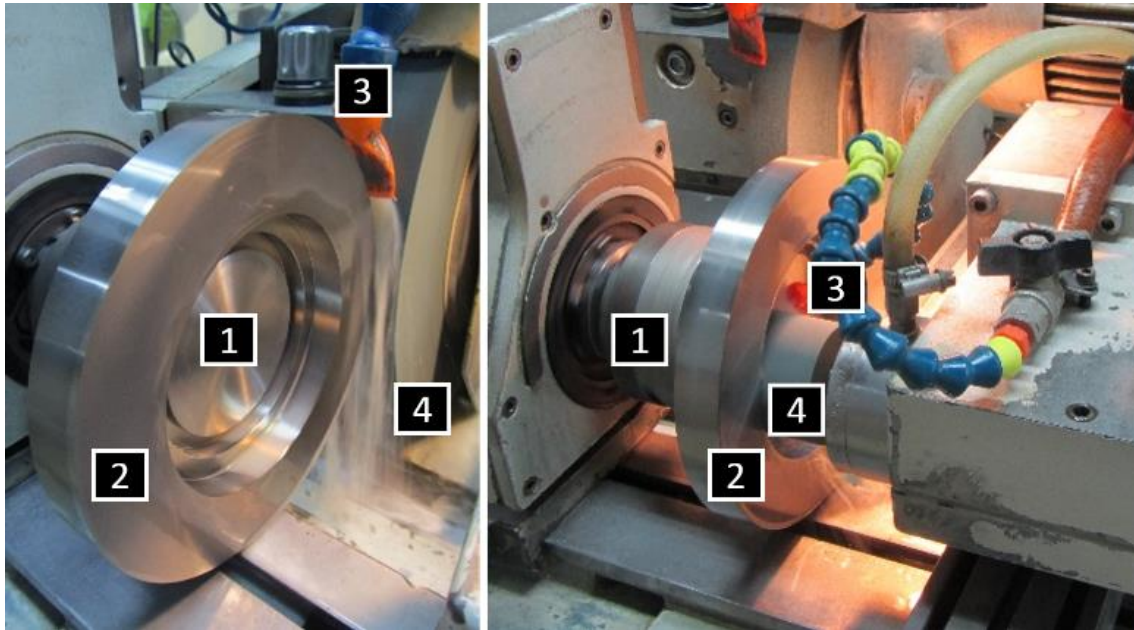


Figure 7-7: Grinding of the titanium rotor version 1
the chuck (1), the rotor (2) and the grinding wheel (4) are shown
along with the coolant (3) which is applied externally or internally.

During grinding, the workpiece was not cooling down in the same way as a solid titanium part would as the heat could not diffuse in the depth of the material.

As the rotor had an elliptical shape, the thickness of the walls was not consistent around the part. Because of that, the titanium alloy was melting and burning differently at different angular positions during grinding, which affected the machining quality.

The subsequent deposition of melted titanium on the grinding wheel was further affecting the work. Subsequently, the wheel had to be often reground.

The water coolant was sprayed either on the outer surface of the rotor being ground, or inside the rotor through the wall left opened with powder removal intents (numbered 3 in Figure 7-3), to enable the grinding, as can be observed in Figure 7-7. Changing the grinding wheel reduced the deposition of melted titanium, bringing better results on the external cylinder of the rotor, reported in Table 7-1 below. The cylindricity, perpendicularity and planarity obtained on the external surfaces after grinding were approaching the required 2 μm tolerances.

Nevertheless, because the minimum spinning speed of the wheel of the Studer S20 grinding machine was higher than the speed required to process the inner cylinder, the part was heating up such that the surface was burning and the workpiece was getting distorted.

Following grinding trials it was concluded that the tolerances would never be achieved and the idea of grinding the rotor was abandoned.

7.3.2 Turning

During turning, the full rotor was held in a NAKAMURA-TOME SC-250 lathe from 2012, equipped with a cutting insert for titanium. As little force as possible was applied by the chuck to hold the rotor. The external cylinder, the face and the internal cylinder were machined without unmounting the part. The results were slightly worse after turning on the external surfaces compared to grinding. The flatness was affected by a residual conical error at the micrometric level. Nevertheless, the turning experiments were successful, as reported in Table 7-1. The two rotors were below the 500 g mass limit.

7.3.3 Notch cutting

After manufacturing the second version of the rotor, the first version was opened by electrical discharge machining in order to observe the amplitude of the deformations due to residual stresses after machining. The notch appears in Figure 7-8. The symmetry introduced in the design, the notch perpendicular to the laser path and the stress releasing heat treatment must have almost eliminated the residual stresses before machining. Nevertheless, the machining, most probably the heat produced during grinding, caused significant residual stresses. As a result, the cutting process moved the rotor's flat surface from a conical form with a few micrometres peak-to-valley deviation to an asymmetrical form with a peak-to-valley deviation larger than two tens of micrometres, as appears in Figure 7-9. However, the form deviation of the external cylinder was increased by two micrometres only.



Figure 7-8: First version of the rotor, after turning and notch cutting

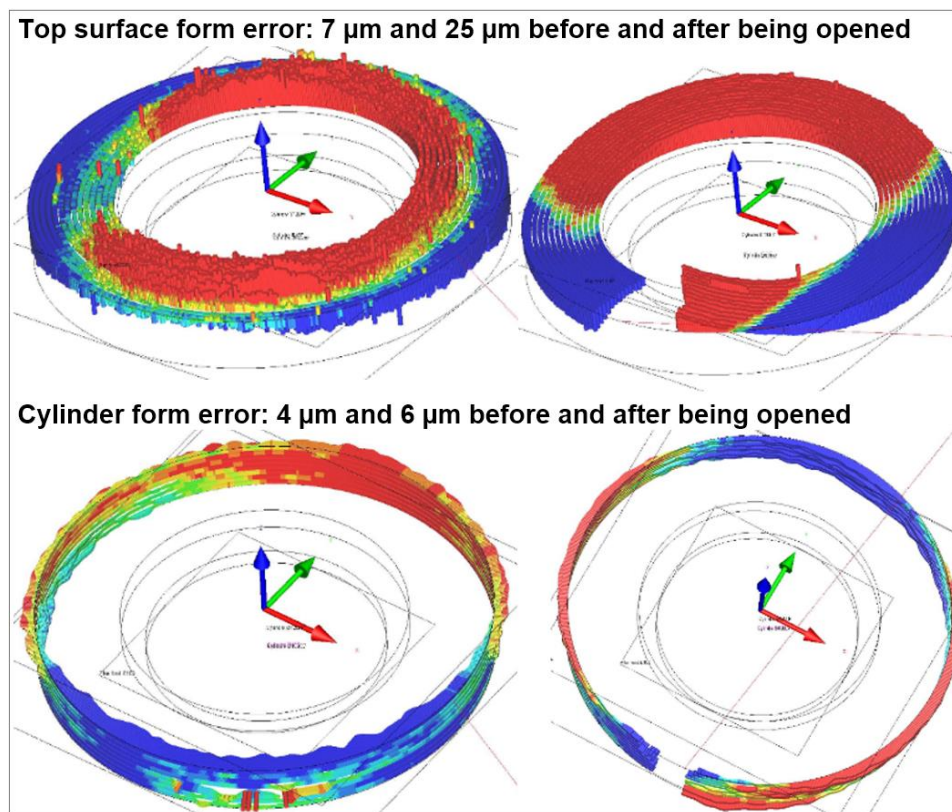


Figure 7-9: Rotor form measurements before and after being opened

As a result, the surfaces of the rotor were out of the acceptable limit of 5 μm and therefore could not be used for the SESHAT. In order to assemble the SESHAT and validate its different components, the notch cutting of the second version of the rotor may be performed as the completion step of the SESHAT – when all the other elements will be properly assembled and operational. Turning generates less heat than grinding, so the stress release by notching is expected to have a reduced impact on the form of the second sample.

7.3.4 Summary of results

	Version 1	Version 2
Nominal wall thickness + excess	1 mm + 0.5 mm	1 mm + 1 mm
After SLM	Semi-minor axis < nominal	Acceptable distortions
	Support structure intact	Broken support structure
Use	Tests and tuning	Composes the SESHAT
During grinding	Surfaces were burning, cylinder $\varnothing 120$ distorted	-
After grinding	Cylindricity $\varnothing 192$: 3 μm	-
	Perpendicularity: 2 μm	-
	Flatness: 5 μm	-
After turning	Cylindricity $\varnothing 192$: 4 μm	Cylindricity $\varnothing 192$: 3.8 μm
	Cylindricity $\varnothing 120$: 7 μm	Cylindricity $\varnothing 120$: 6.7 μm
	Perpendicularity: 10 μm	Perpendicularity: 2.5 μm
	Parallelism: 5 μm	Parallelism: 2 μm
	Flatness: 7 μm	Flatness: 2 μm
After EDM notch cutting	Cylindricity: 6 μm	-
	Flatness: 25 μm	-
Mass after machining	357 g	450 g

Table 7-1: Recapitulation of the results
obtained for the different versions of the rotors before and after grinding, turning and cutting

The measurements with the results after SLM, reported in Figure 7-6, were performed with a calliper. The form deviations after grinding, turning and notch cutting, reported in Table 1, were measured with a Leitz Infinity CMM with a $\text{MPE}_E = 0.3 \mu\text{m} + L/1000 \mu\text{m}$ (with the length L in millimetres). The visual measurements results shown in Figure 7-9 were obtained with an O-Inspect with a $\text{MPE}_E = 1.9 \mu\text{m} + L/300 \mu\text{m}$ (with the length L in millimetres).

7.4 Conclusion and discussion

This chapter explored the production of a Ti-6Al-4V high-precision rotor using additive manufacturing. The objective of the research was to obtain a light air

bearing rotor adapted to a high precision mechanical assembly. The work was divided into the following tasks:

- adapting the drawing to additive manufacture and obtain a rotor compatible with further machining,
- define the best machining technique and strategy to reach the tolerances,
- observe the consequences of the actual machining on the assembly,
- observe the consequences of notching.

7.4.1 Adapting a technical drawing for additive manufacture

The proposed solution minimises potential distortions due to AM induced thermal stress by setting the laser path of the SLM device perpendicular to the notch plane.

The functional technical drawing initially designed for the SESHAT was adapted to AM by oversizing the dimensions. However, the first trial produced a too small workpiece due to the distortions induced by the SLM technique on large parts. To address these AM issues, two approaches were possible: either distorting the CAD in order to compensate for the distortions of the machine, or increase the machining margins. The latter was chosen in this research work.

7.4.2 Adapting traditional machining techniques to a hollow part

Given the lack of appropriate AM net shape precision and surface roughness quality, two subtractive machining techniques have been tested to finish the part, grinding and turning, respectively.

During grinding, the thin walls of the outer cylinder brought problems of heat transfer leading to the melting of the titanium alloy, which also altered grinding wheel properties. To overcome this situation, the coolant was inserted inside the opening of the rotor. The AM requires an opening into the workpiece to facilitate the extraction of un-melted powder. This opening can be used to regulate the temperature of the workpiece.

Nevertheless, as not enough time was available to research further in this direction, grinding operation was replaced by turning.

A second rotor, featuring larger walls, was turned to the dimensions: 2 μm tolerances were reached on the flatness and perpendicularity, and the cylindricity deviation on the external cylinder was within the 5 μm limit allowing the air bearing to work, despite not in optimal conditions (see section 5.2). The results on the inner cylinder were out of tolerance, they are discussed in the next section 7.4.3.

Machining techniques, which rely on heat diffusion in the material, have to be very carefully considered when applied to parts produced by additive manufacturing with thin walls for high precision applications.

In conclusion, grinding generated excessive non-uniform heat, which induced thermal stresses that led to out of tolerance errors after the rotor was sectioned. Turning trials did not generate excessive heat, and it was selected to produce the final shape, form and texture of the lightweight rotor.

7.4.3 Adapting the functionality of the part to the limitations of the resulting workpiece

The inner cylinder of the SESHAT rotor cannot be used as intended due to its 7 μm of cylindricity (see section 5.2): larger than the 2 μm tolerance for optimal use and the 5 μm tolerance for possible use. The air pads on the inner cylinder were added in order to increase the stiffness of the assembly. The cylindricity of the outer cylinder is larger than tolerated for the optimal use of the bearing. To allow the bearing to be mounted nonetheless, an increase of the air gap was required. This leads to a reduction of the stiffness of the assembly. Suppressing the inner air pads may reduce the stiffness more than it is acceptable for obtaining the high repeatability of the SESHAT. This is to be determined by experimental tests.

7.4.4 Consequences of notching and stress release

Despite optimising the design and heat treatment of the rotor, opening the test part engendered distortions adding 18 μm to the flatness and 2 μm to the cylindricity. A part with such distortions could not be used for the SESHAT, nevertheless, it illustrates the possibility of opening a part obtained by additive manufacturing if the functional surface is the external cylinder of a SESHAT-rotor-

like part. The study of the SESHAT shall be continued with the second rotor non-opened.

7.4.5 Further work

Simulations could be performed in order to enable high precision machining of cylindrical hollow parts ensuing additive manufacturing. The simulations should find the inner shape of a workpiece that allows for optimal cooling during the finishing process. This research would target the determination of the different forces resulting from the movement of the liquid inside the spinning workpiece subject to the centrifugal force. The inner walls should aim at facilitating the optimum movement of the coolant which should reach the targeted surface to be cooled before being extracted from inside the workpiece as it becomes warmer. This strategy might overcome the distortions added by the speed limit of the wheel of the grinding machine, which led, in this study, to the distortion of the entire part.

CHAPTER 8 CONCLUSION AND FUTURE WORK

8.1 Conclusion

The research presented in this thesis is part of a project funded under Marie Skłodowska-Curie Innovative Training Network, called Particle Accelerator Component's Metrology and Alignment to the Nanometre scale (PACMAN).

CERN currently is looking to develop new accelerating structures, such as the Future Circular Collider (FCC) or the Compact Linear Collider (CLIC), to enable future research in high energy physics. One of the challenges of the CLIC is to keep a high density of particles in the beams along its length, which relies on precise alignment of the component of the accelerating structures. The magnets fiducialisation is an integral part of the CLIC alignment process. The aim of the magnet fiducialisation is to express the position of the zero axis of the magnetic field in a coordinate system based on the fiducials installed on the magnet's external parts. This is done in a metrology lab using a CMM and the stretched wire technique by measuring the wire position with respect to the fiducials.

The research work summarised in this thesis aimed to design a sensor enabling the Leitz Infinity CMM ($MPE_E = 0.3 + L/1000 \mu m$) to perform non-contact measurements on the PACMAN reference wire to permit its axis positioning with an uncertainty such that $3\sigma < 0.5 \mu m$. The proposed solution was the Shape Evaluating Sensor: High Accuracy and Touchless (SESHAT) (Figure 1-8) which is a non-contact form measuring sensor. The validation of the design required closing several knowledge gaps. To achieve the overall aim of the work several objectives were defined and the work is briefly concluded in next paragraphs.

The first objective was to determine whether the wire used to fiducialise the CLIC quadrupole magnets, accelerating structures and beam position monitor, was suitable for these tasks. This objective was achieved (Table 4-1) and the choice of a copper-beryllium wire with a diameter of $100 \mu m$ was validated for these tasks. Nevertheless, a large form error ($> 2.4 \mu m$) varying along its length may increase its axis positioning uncertainty.

The second objective was to design the SESHAT (Figure 1-9). This objective was fulfilled as the design of the SESHAT is completed and different elements were tested. The chromatic confocal sensor was validated on the wire, the air bearing was tested and approved, the feasibility of the rotor was tested and discussed, the actuator and other components was selected.

The third objective consisted in predicting the behaviour of air pads over an opening in the bearing surface (Figure 6-2). A mathematical model was proposed and validated against actual measurements (Figure 6-13). This model was also fulfilling a gap of knowledge and led to a research paper (Appendix D), which is yet not published at the time these lines are written. The model can be used in the future to predict and compensate the systematic errors introduced by the stiffness reduction due to the opening in the rotor.

The fourth objective was to demonstrate the feasibility of high precision machining of a part created by additive manufacturing. The precision obtained on the rotor created by additive manufacturing was not sufficient to fulfil the 2 μm tolerance on the form of the SESHAT rotor (Table 7-1), nevertheless, the work describing precision machining of complex rotary shape created by selective laser melting was published in *Additive Manufacturing* (a peer reviewed journal). This answered the question of the suitability of additive manufacture to perform high precision parts (form error < 7 μm achieved on two flat sides and two cylinders) with improved performances, consequently closing another gap of knowledge.

The last objective aimed to quantify the measurement uncertainty resulting from the use of a chromatic confocal sensor (with a measurement range of 100 μm , see Table 4-3) rotating around a stretched wire. The measurement uncertainty was performed for a wire on a rotary mount being measured by a static chromatic confocal sensor (Figure 4-12). The typical 321 nm standard uncertainty obtained on the form error evaluation of the PACMAN wire (Table 4-5) was validating the general concept of the SESHAT. The results were published in *Measurement Science and Technology* (a peer-reviewed journal).

8.2 Contribution to knowledge: Papers and Presentations

Several presentations, posters and conference papers were written and presented to introduce the ideas and the processes described in this thesis to the scientific community (acronyms are detailed at the end of the list):

- CIM¹ 2015: Paper and oral presentation
Characterisation and measurement to the sub-micrometre scale of a reference wire position.
Claude SANZ, Ahmed CHERIF, Hélène MAINAUD DURAND, Paul MORANTZ, Paul SHORE
DOI: <https://doi.org/10.1051/metrology/20150013005>
- EUSPEN² 2015: Paper and poster presentation
New potential for the Leitz Infinity Coordinate Measuring Machine
Claude SANZ, Ahmed CHERIF, Hélène MAINAUD DURAND, Jürgen SCHNEIDER, Norbert STEFFENS
URL: <https://cds.cern.ch/record/2038138/>
- IBIC³ 2015: Paper co-authorship
Status of the PACMAN project.
Kurt ARTOOS et al.
URL: <http://cds.cern.ch/record/2148408/files/CERN-ACC-2016-0027.pdf>
- 2016 IEEE⁴ Sensors Applications Symposium: Paper co-authorship
Sensors applications within the research framework of the PACMAN project on metrology for particle accelerators at CERN.
Pasquale ARPAIA et al.
DOI: 10.1109/SAS.2016.7479854
- EUSPEN² 2016: Paper and poster presentation
Rotating sensor for new possibilities on Leitz Infinity Coordinate Measuring Machine.

Claude SANZ, Ahmed CHERIF, Hélène MAINAUD DURAND, Kurt ARTOOS, François MOREL, Paul MORANTZ, Paul SHORE, Jürgen SCHNEIDER, Norbert STEFFENS

URL: www.euspen.eu/knowledge-base/ICE16-P1.18.pdf

- Introduction to Metrology for all ages and background (11/2016): oral presentation

La Science de la Mesure : La Métrologie. **Claude SANZ**

URL:

https://indico.cern.ch/event/587067/contributions/2365713/attachments/1369202/2075720/La_science_de_la_mesure_C_SANZ_08112016.pdf

- IWAA⁵ 2016: Paper and oral presentation

A rotary mount for positioning a stretched wire axis within a coordinate measuring machine.

Claude SANZ, Ahmed CHERIF, Hélène MAINAUD DURAND, François MOREL, Jürgen SCHNEIDER, Norbert STEFFENS

URL: <https://cds.cern.ch/record/2243575/files/CERN-ACC-2017-0004.pdf>

- 2017 Physical review accelerators and beams: Paper co-authorship
New solution for the high accuracy alignment of accelerator components.
Hélène MAINAUD et al.

URL: <http://inspirehep.net/record/1469516/files/moocb01.pdf>

- 2018, Measurement Science and Technology, Vol. 29, Issue 7: Paper
Form measurement of a 0.1 mm in diameter wire with a chromatic confocal sensor, with the associated uncertainty evaluation.

Claude Sanz, Claudiu Giusca, Paul Morantz, Antonio Marin, Ahmed Chérif, Jürgen Schneider, Hélène Mainaud-Durand, Paul Shore, Norbert Steffens

ISSN: 0957-0233

- 2018: Additive Manufacturing: Vol 23, Pages 287-293: Paper
Micro-scale surface and form finishing of a Ti-6Al-4V lightweight rotor obtained by selective laser melting used for air bearing.
Claude Sanz, Romain Gérard, Paul Morantz, Ahmed Chérif, Paul Shore, Hélène Mainaud-Durand, Alexander Lunt
DOI: <https://doi.org/10.1016/j.addma.2018.05.033>
- Last research article: complete manuscript, not published yet
Model of porous-air-pad load variation over a through hole.
Claude Sanz, Paul Morantz, Alexander Lunt, Ahmed Chérif, Paul Shore, Jürgen Schneider, Hélène Mainaud-Durand, Norbert Steffens

¹ International Metrology Congress

² European Society for Precision Engineering and Nanotechnology

³ International Beam Instrumentation Conference

⁴ Institute of Electrical and Electronics Engineers

⁵ International Workshop on Accelerator Alignment

8.3 Discussion and future work

Most of the manufacturers' specifications are evaluated in the best possible laboratory conditions, which may not apply in during real applications. For instance, the axial stiffness brought by the air pads seems large compared to the minimum stiffness required for the piezoelectric actuator, nevertheless, if the air pads are not at the nominal distance of 5 μm from the bearing surface, the stiffness can vary dramatically (see Figure 6-12) and become smaller than the minimum required. Another concern is that the piezoelectric actuator should never encounter the resonance frequency of the bearing shaft (5.11), therefore, it should be actually evaluated before the actuator installation. Additionally, some elements are missing in the current model of the SESHAT, namely, all the elements used for attaching the pipes and wires to the stator (so that they do not

interfere with any of the rotor's position) and the elements to lead the optical fibre of the Precitec sensor around the rotor and stator.

The result from equation (5-B), from which is derived the actuator's requirement on strength, is given as an indication to show how little was the strength required for the actuator (7 mN). Readers used to actuators dimensioning may argue that the resistive forces should be taken into account in this computation – whereas they are not. By design, the actuator is moving the rotor within the air bearing in a direction in which the resistance is negligible (6.1), hence, the resistive forces were neglected. The mass of the optical sensor (36 g) was neglected as well in this computation. As discussed in the previous paragraph, the mass of the sensor can be compensated for, but it will have an impact on the inertia. Although the resistance of the optical fibre to deformation is not taken into account in the calculation, it can affect the sensor performance. As the tightening features are not decided yet they were not evaluated either. These elements all influence the result.

Table 5-4 shows how over-dimensioned the actuator is ($\times 1000$). The reason for the choice of this actuator is that it is the smallest piezoelectric actuator featuring two legs, which touch alternatively the ceramic bearing surface and thus should reduce the amplitude of the vibrations during operation. Nonetheless, this point is not mentioned by the provider who has not assessed the amplitude of the vibrations either.

8.3.1 The measurement strategy with the SESHAT

The initial PACMAN measurement strategy was based on the assumption that the wire is a straight line. According to the catenary equation, this assumption would bring an uncertainty in the result reaching maximum 10 μm (in the middle of the wire, zone hidden inside the magnet), which is a function of the measurement position. To compensate for this, the points measured on the wire should be spread as much as possible and then the catenary fitting algorithm should be used to find the position of the wire axis with a reduced uncertainty.

There are two measurement strategies that can be used with SESHAT.

Due to the stepping nature of the piezoelectric actuator, one measurement strategy is to be static during the measurement and to average a number of acquisitions for each position. The motivation for this approach is that the results' quality would be improved if all the elements are in equilibrium. Nevertheless, there are several points to take into account before concluding on this matter: When will be such a complex assembly in equilibrium? For how long should one wait before taking a measurement? As the air pads are cooling the rotor while the actuator is warming it up elsewhere, can the thermal equilibrium be achieved?

The second measurement strategy is to synchronise the piezoelectric actuator and the optical acquisition. If the points are taken when the actuator is moving in the same direction, some of the systematic errors can be compensated. Nevertheless, this approach is also raising questions: As the optical sensor is rotating, would it make sense to consider that the motion of a rotor which is either on one side of the sensor or on the other, is having the same impact on the measurement? Would the propagation of the stress through the material desynchronise the measurements?

To answer all these questions further tests will be required, as there are no models that can account for all interfaces of the SESHAT and are able to predict with enough accuracy the effects of thermal and mechanical behaviour induced by the air bearing.

Once the SESHAT will be mounted, the number of points missing on the circle for the roundness measurement should be assessed, from which should be derived the corresponding contribution to the uncertainty on the form evaluation.

The roundness is probably not what the operator of the Leitz Infinity CMM will use to define the threshold validating or not the position quality. Indeed, the final aim of the measurement is to evaluate the position of the centre of the wire. This position may be affected by the form deviation, or not. If the wire is elliptic at the measurement position, it is not a problem for the operator. But, if there is a piece of dust on the wire's surface which is shifting the position of the centre, then the operator will want to use a further position on the wire to perform the measurement. In other terms, in order to evaluate the suitability of the position of

the measurement, the operator should check the form of the wire surface. To do so, he needs the complete measurement information. For this purpose, the filter applied to the raw acquisition should be such that a form of 6 μm can be observed on the wire, as it is the limit which would bring the position of the centre out of tolerance.

Considering the small size of the wire, form measurement on this wire corresponds to waviness or even roughness measurements as they are usually described in the standards. The validation of the measurement was performed on the rotary table. Nevertheless, the validation of the sensor for the wire measurement should be performed also by comparison between a roughness measurement system used as a reference and the chromatic confocal sensor.

8.3.2 The wire form deviation measurement strategy and conditions

The results obtained by applying the methodology described in this thesis, coupled with the environmental conditions of the CERN laboratory and the care of the operator, showed that it is possible to measure the roundness of very small samples, such as the PACMAN reference wire. The obvious limitation of this design is that the measured surface deviation added to the misalignment contribution cannot be larger than the measuring range of the sensor. Additionally, these measurement results should be well defined before being called roundness, as the standard defining this terminology was not followed: the wire diameter is too small to apply the prescribed filters parameters.

The methodology described in this thesis for the uncertainty evaluation can be adapted to many different samples and sensors. Larger form deviations can be measured with a non-contacting sensor having a larger measuring range (which is very often linked to a larger uncertainty).

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APPENDICES

Appendix A Wire characterisation measurements

The properties required by all the users of the wire were gathered and no material was found better than CuBe for performing the fiducialisation measurements. The wire is photographed on a granite table in Figure 9-1.



Figure 9-1: Microscope view of a Ø100 µm copper-beryllium wire

A.1 Electrical property: resistivity

The electrical resistivity ρ is a characteristic useful for the electrical measurements (for BPM and accelerating structures characterisation). It has been measured using an Agilent 4263B LCR metre with a 16047E test fixture. This test fixture aims to reduce the measurement errors due to lead impedances, allowing measurements of lower impedances. Emphasis was placed on the connection between the wire and the test fixture, as can be observed in Figure 9-2. The acquisition provided the resistance R of the wire. Afterwards, the resistivity ρ was derived from the length L and the section S with an uncertainty below 1% using the equation (9-A). This uncertainty was acceptable as it would not bring the results of $8.35 \mu\Omega\cdot\text{cm}$ and $10.86 \mu\Omega\cdot\text{cm}$ out of the tolerance of $15 \mu\Omega\cdot\text{cm}$ (see Table 4-1Table 2-1).

$$\rho = \frac{R * S}{L} \quad (9-A)$$

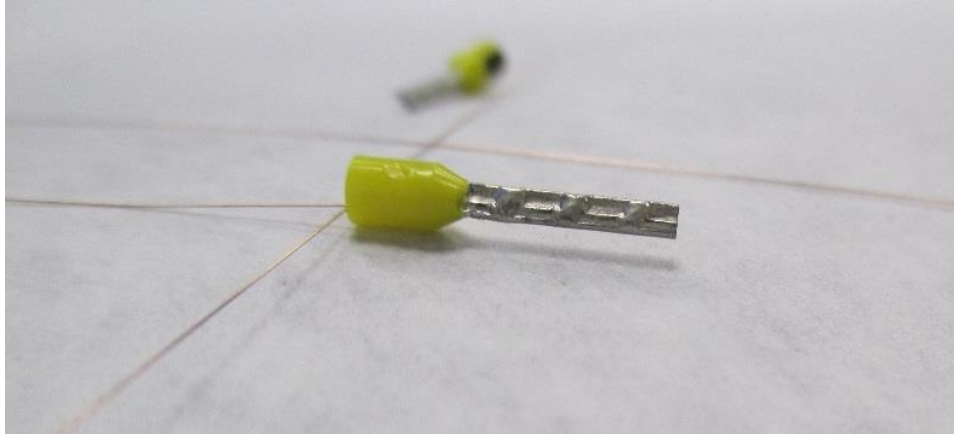


Figure 9-2: Wire sample prepared for resistance measurement

A.2 Mechanical properties

A.2.1 Limit tension and yield strength

These measurements were performed by author's colleagues and are not part of the research work, however, summary of results are presented here for completeness. The wire was too small to be held in a common way by the machine's tweezers. To evaluate the limit tension of the wire, both ends of the wire were rolled around a trundle and then the wire was pulled apart by the UTS 200 pulling system while the tension was measured by the GTM strength cell of 1 kN with its uncertainty of 1 %. Three samples from CFW Company were measured and the wire reached an average limit tension of (15.20 ± 0.18) N. From this measurement, the wire yield strength of (1145 ± 14) MPa was deduced.

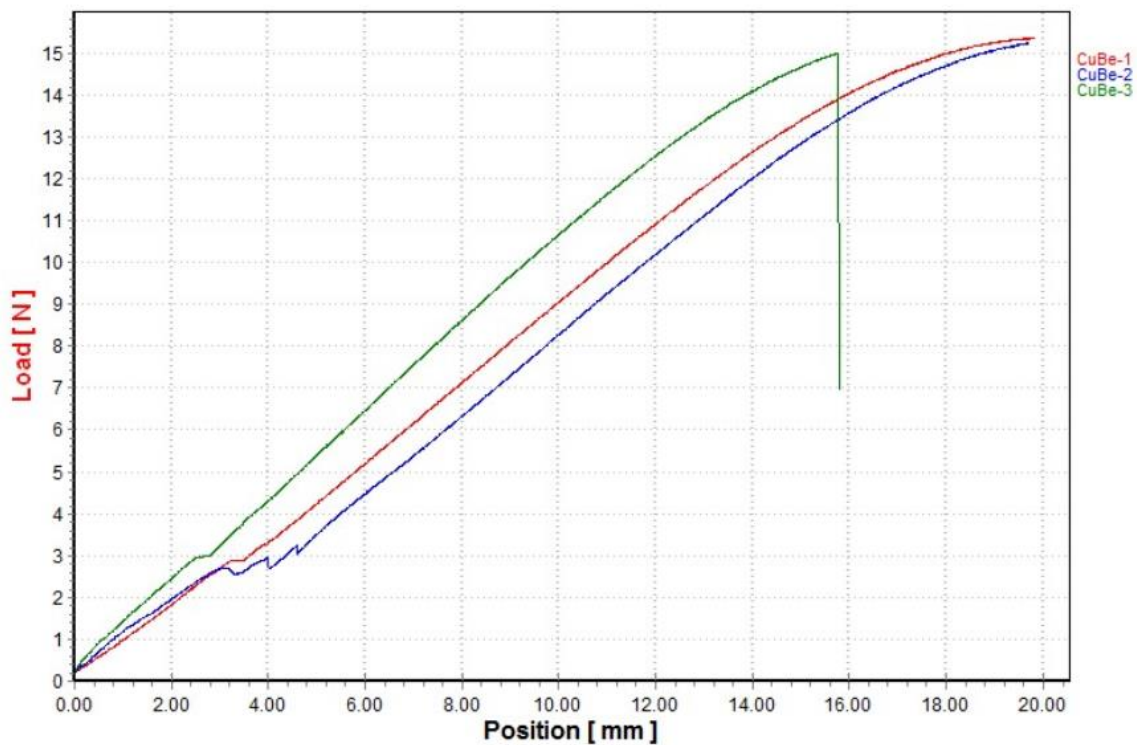


Figure 9-3: Three measurements were performed to determine the limit tension.

A.2.2 Micro-hardness

A special preparation was needed for the micro-hardness measurement. Two pieces of wire were Nickel coated in a 50 °C bath for an hour. They were then stretched using two aluminium plates. The bottom aluminium plate was then placed in a resin. The wire embedded in the resin was polished to the micrometre-level after being cut (see Figure 9-4). The surface of the prepared sample was punched by the Wolpert Wilson 402 MVD with a force of 50 gf (see Figure 9-5). The dimension of the dent, acquired after a magnification with an objective $\times 40$, leads to the values of 357 Vickers for the wire micro-hardness – with an accuracy of ± 10 Vickers.

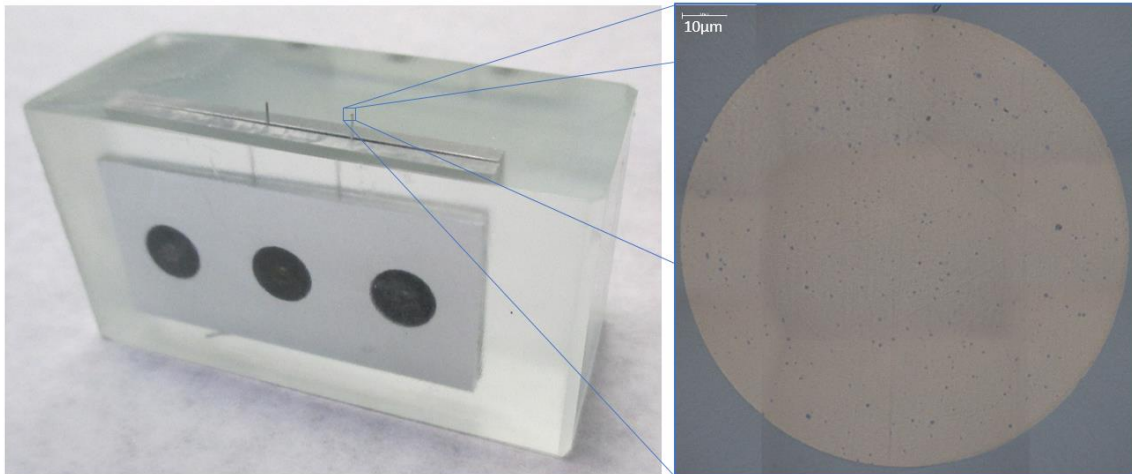


Figure 9-4: PACMAN wire caught in resin and polished, right image acquired with a microscope and stitched

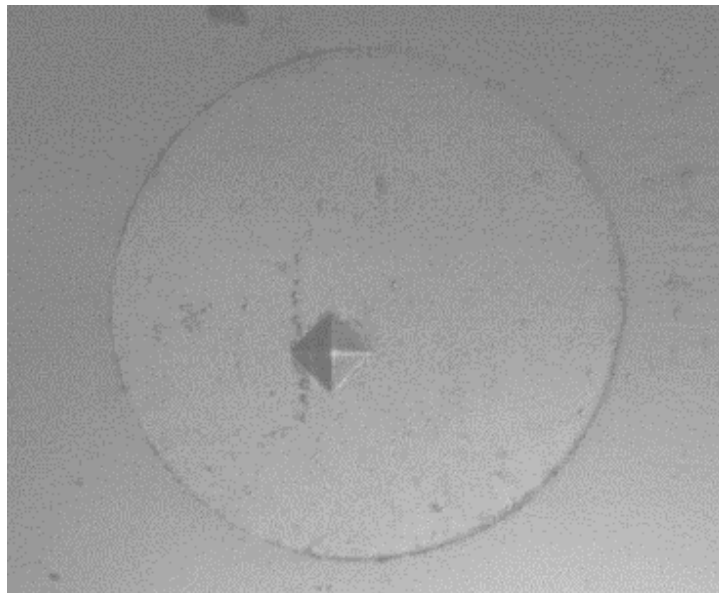


Figure 9-5: Impact of the punch on the wire surface for micro-hardness measurement

A.2.3 Linear mass

To obtain the linear mass, the wire length of $(7\,540 \pm 2)$ mm was obtained by rolling the wire around a 120.003 mm diameter cylinder; the wires were then weighted at 0.5002 g (CFW) and 0.4974 g (GF) using a Mettler Toledo XP204 weighting device with 0.1 mg uncertainty, leading to linear masses of 66.34 mg/m and 65.97 mg/m.



Figure 9-6: Roll of 7.540 m of copper-beryllium wire obtained by winding it around a cylinder gauge, to be weighted by a chemistry scale

A.3 Optical properties

A.3.1 The spectrometric reflectance

The spectrometric reflectance of the wire was measured using a Perkin Elmer LAMBDA 650, with an integrating sphere having a diameter of 150 mm. The incoming light was reflected on the sample appearing in Figure 9-7, this reflected light was collected by the sphere and spectrally analysed to give the reflectance for the different wavelengths of the light. This device has a measurement uncertainty of about 1 % for the visible light ($300 \text{ nm} < \text{wavelength} < 800 \text{ nm}$). The curve of the spectral reflectance appears in the recapitulative Table 4-1.

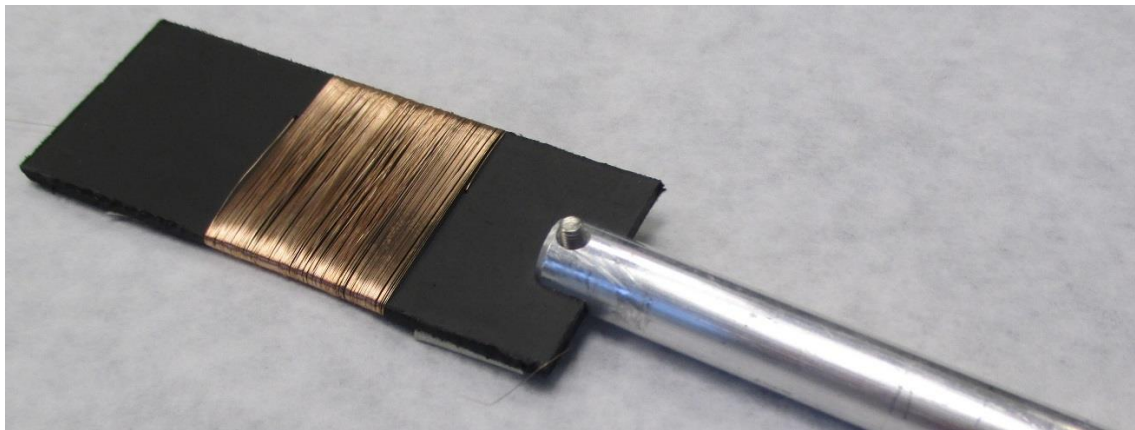


Figure 9-7: Wire wound around a black support for optical properties evaluation

A.4 Dimensional properties

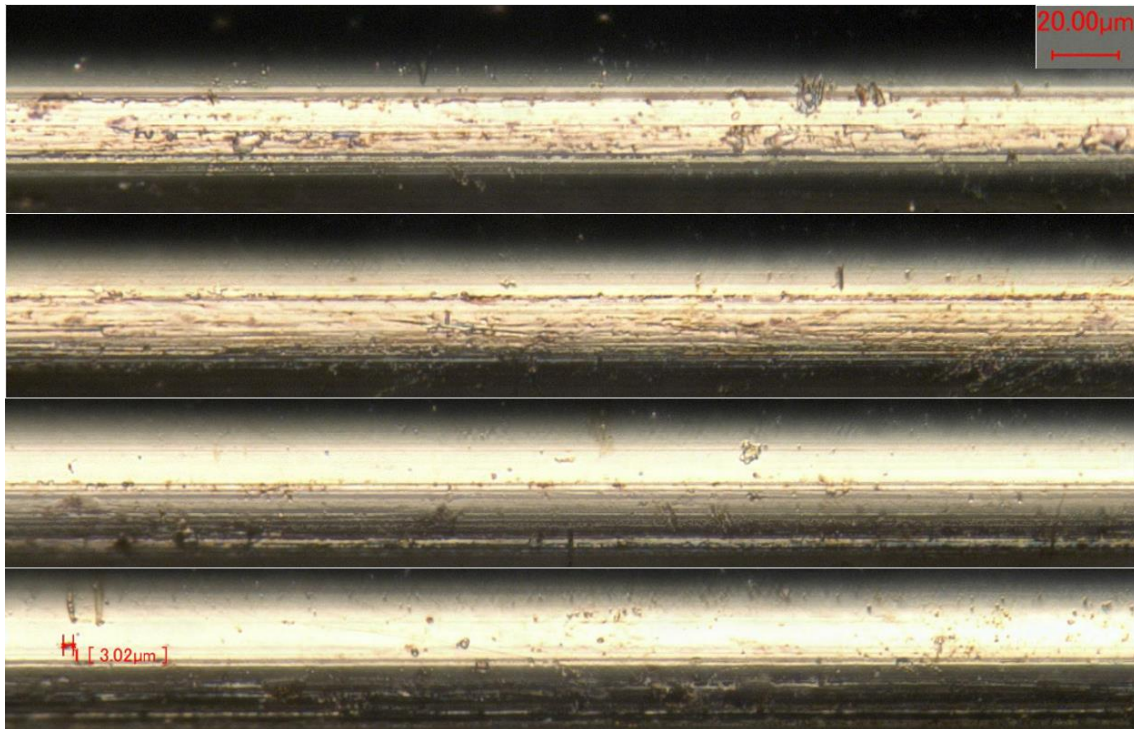


Figure 9-8: Microscope images of the wire showing the irregularities on the surface

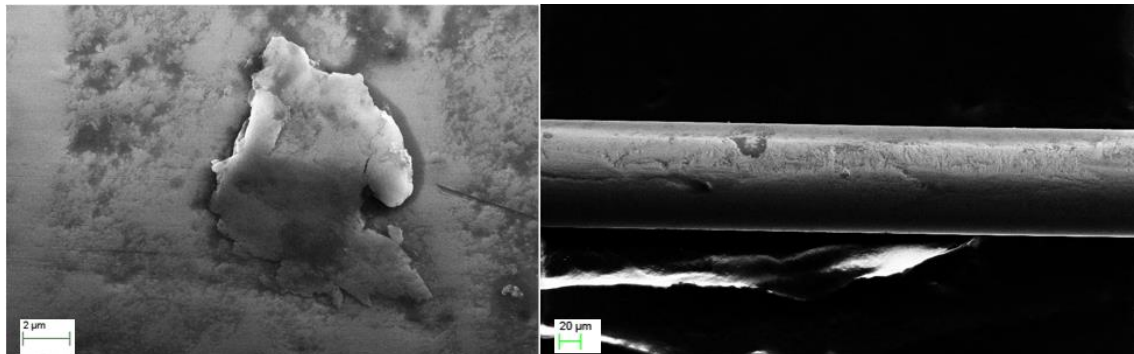


Figure 9-9: Atomic Force Microscopy of the wire showing pieces of dust

The irregularities observed in the optical and atomic force microscopes images of the wire, appearing in Figure 9-8 and in Figure 9-9 respectively, motivated further investigations in the domains of dimensional measurements before the wire could be validated as a suitable for being the reference for the PACMAN project.

A.4.1 Diameter measurement

The diameter of the wire was measured using a KEYENCE optical micrometre LS-9006 with an uncertainty of $0.5\text{ }\mu\text{m}$. 25 measurements were performed randomly along 10 m of wire leading to $98.5\text{ }\mu\text{m}$ of average diameter for the California Fine wire samples and $99.2\text{ }\mu\text{m}$ of average diameter for the Good Fellow samples.

A.4.2 Surface roughness comparison measurements

The roughness measurements were performed at Cranfield University using an Atomic Force Microscope Bruker Dimension 3100: random areas of the wire were scanned, with a size of $20\times 5\text{ }\mu\text{m}^2$ (see Figure 9-10). The resulting small areas were analysed using the software Nanoscope Analysis from Bruker allowing to perform cross-sections perpendicular to the wire axis. The uncertainty of the technique applied to this measurement was given lower than 5 nm by the operator. Nevertheless, the results given for the roughness deduced from these measurements are highly dependent on the analysis parameters used in the software. As the aim of the measurements is to compare the wires, no parameters optimisation was performed. This is why the numbers presented in Table 4-1 Table 2-1 are providing valid information for comparison but not for evaluation of the different surfaces roughness.

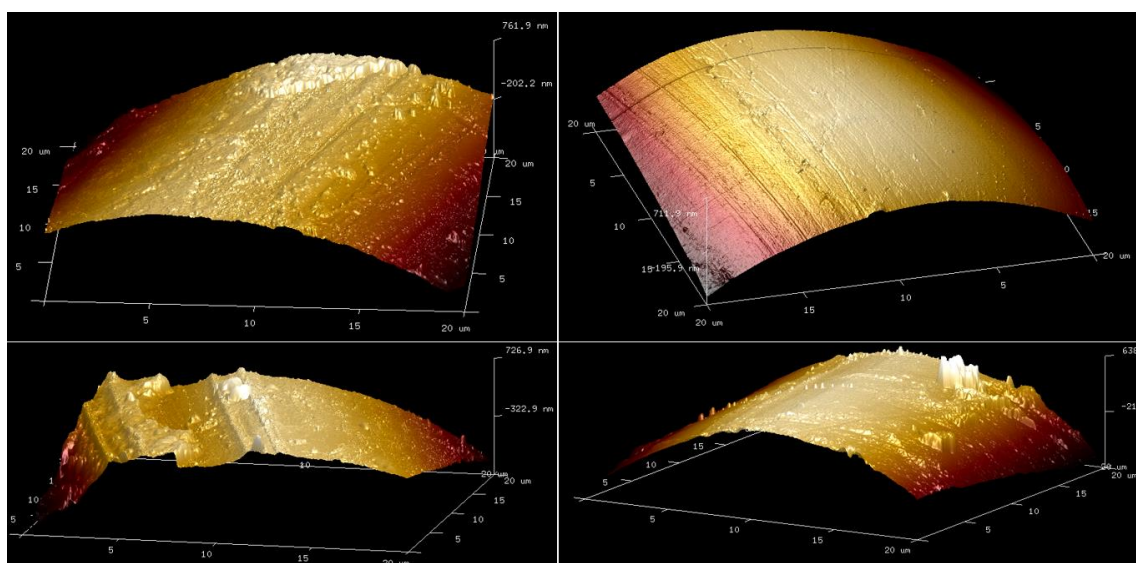


Figure 9-10: Wire surface roughness obtained with an Atomic Force Microscope

A.4.3 Form measurement

The wire surface form measurement is one of the core prerequisite of the research presented in this thesis as it is what brought the need for the SESHAT. An attempt at measuring the form of the wire was done with the team from the company CARY Precision, specialists in gauges manufacture and measurements, in their laboratory in Le Locle in Switzerland. The contacting form measuring device from ELYT was given with an uncertainty of $0.1\text{ }\mu\text{m}$. The wire was stretched between a rotary chuck and a fixed holder while the contacting probe appearing on the photo Figure 9-11 was measuring its deflections. Despite the fact that this measurement system was not optimised for such a thin sample, a few stable measurements could be obtained, nevertheless not enough to obtain neither statistical results nor the assurance of a significantly low level of uncertainty on the results. Similarly, parts of the PACMAN wire were sent to many companies and laboratories to be measured by their best-suited device, but none of them could bring stable results with low uncertainties.



Figure 9-11: Contacting measurement aiming to evaluate the wire roundness

After these infructuous trials, an idea was to use a MarForm measurement system to make a test bench for the wire form measurement. The setup, described in the paragraph 4.5 of the thesis, was twofold: testing the chromatic confocal sensor and evaluating the wire roundness deviation. The aim of the measurements performed on the three wires, presented in Table 9-1, was to compare them with each other. For this purpose, the longer acquisitions were shortened to the length of the shortest: slightly longer than two rotations. The acquisitions were performed at random positions along the wires, on the same day, with similar conditions including an environmental noise with 81 nm of standard deviation. The results appearing in Table 9-1 are given as roundness deviations: they come from the addition of the maximum positive and negative deviations after decentring removal.

	GF	CFW	NGK
Roundness measurement 1 [μm]	22.47	1.37	1.44
Roundness measurement 2 [μm]	1.74	2.31	2.75
Roundness measurement 3 [μm]	2.88	2.39	2.10
Roundness measurement 4 [μm]	3.37	2.89	1.56
Roundness measurement 5 [μm]	3.79	2.00	1.85
Roundness measurement 6 [μm]	8.17	2.08	1.82
Roundness measurement 7 [μm]	2.08	1.26	1.47
Roundness measurement 8 [μm]	0.96	1.25	1.74
Roundness measurement 9 [μm]	1.88	3.50	1.38
Roundness measurement 10 [μm]	1.52	5.53	1.48
Mean [μm]	2.93	2.46	1.76
Standard deviation [μm]	2.04	1.23	0.39

**Table 9-1: Surface comparison of wires from different providers
(Good Fellow, California Fine Wire and NGK)**

The maximum deviation between two data points was obtained following the approached below representing the decentred wire rotation:

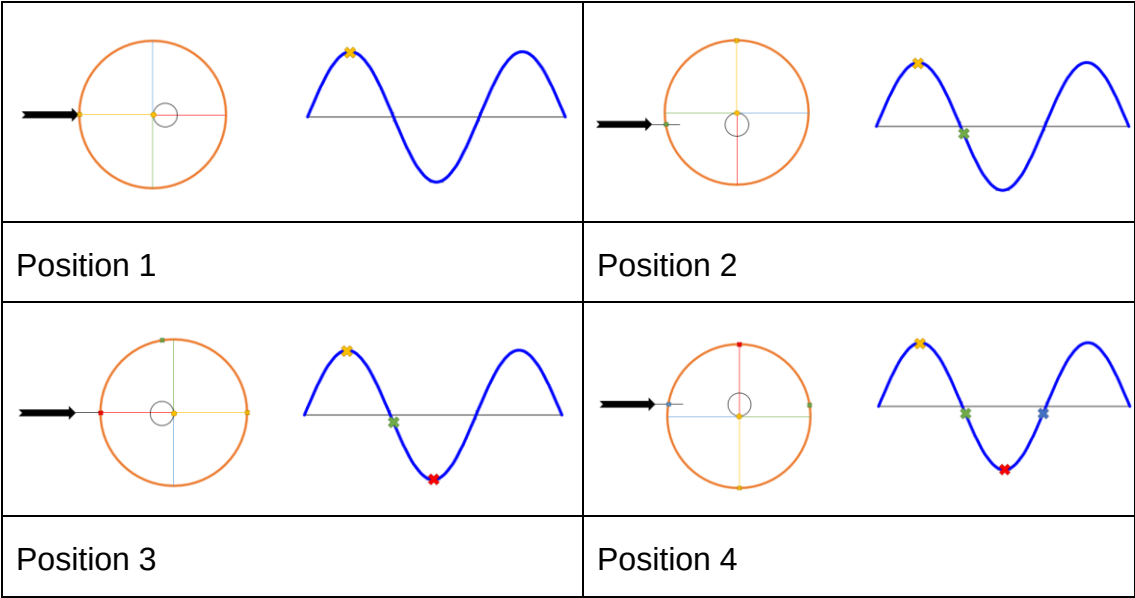
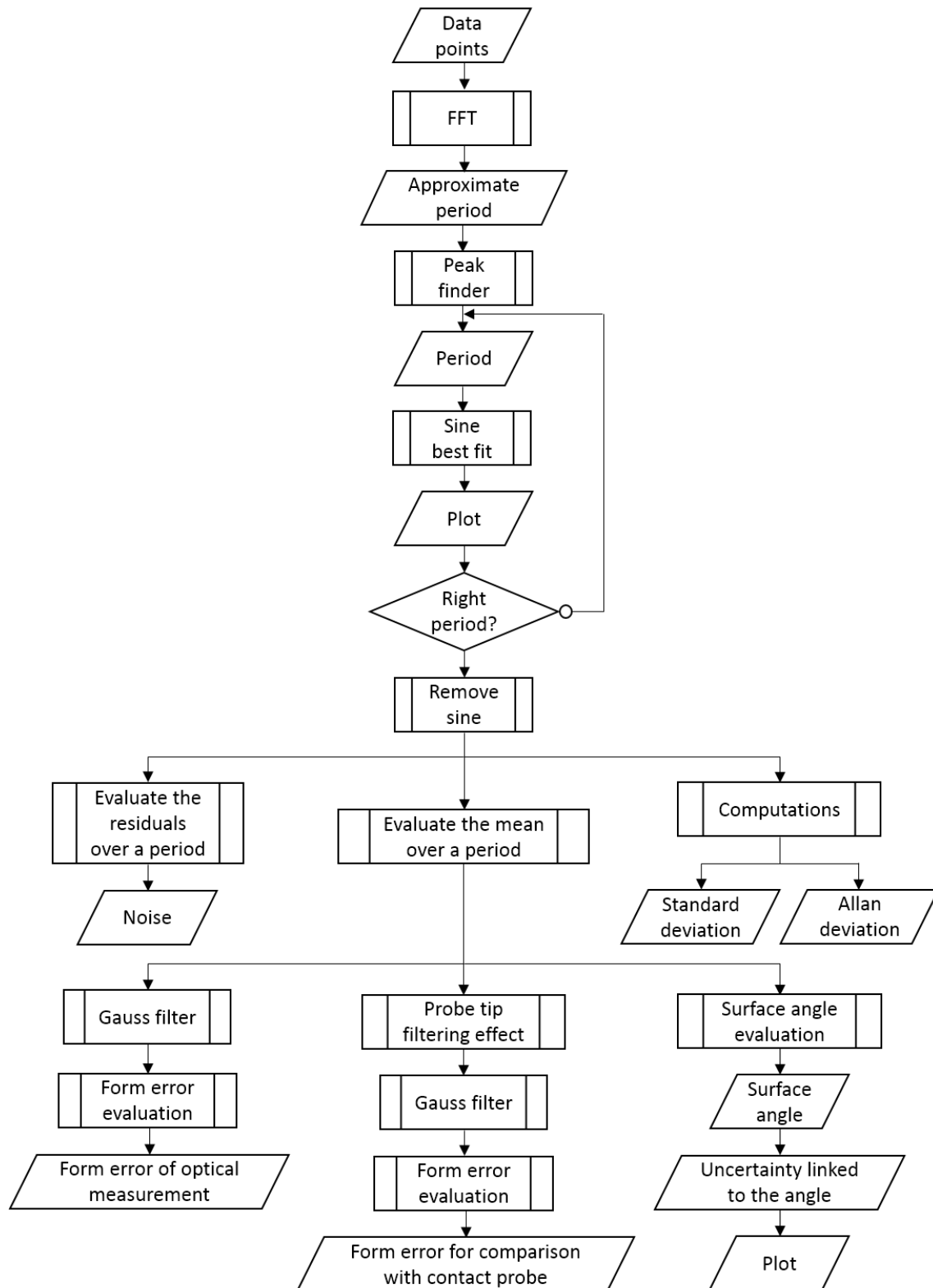


Figure 9-12: 4 measurement data acquired on the wire surface highlighting the nature of the distance variation between two measurement points

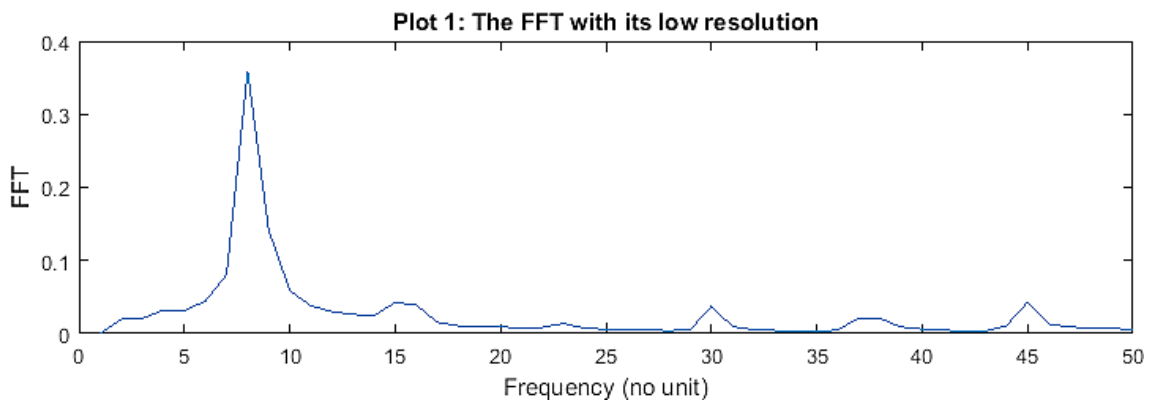
Appendix B Wire form measurement post-processing

B.1 Flow chart

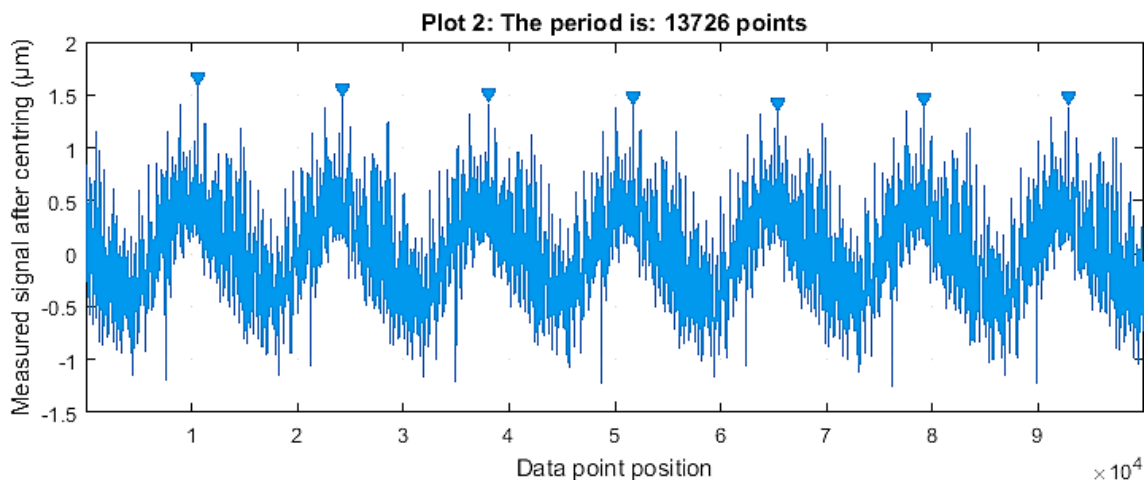


B.2 Application: traceability evaluation

The measurement data obtained by the chromatic confocal sensor on the 5 mm in diameter artefact were loaded into the Matlab routine. The signal was centred: the average of the dataset was subtracted from the dataset. The signal was resampled: the optical sensor acquired more points per length unit than the contact measurement system, in order to compare the points, the number of points of the optical measurement was adjusted to the number of points of the contacting measurement. A Fast Fourier Transform (FFT) was applied to the dataset (see Figure 9-13). The position of the peak is used in order to have a good approximation of the period of the sinusoidal wave.



The approximation of the period is used as the input parameter for a peak finder function, this parameter defines the minimum distance between two peaks to be found. The results of the peak finder function appear in Figure 9-14.



The period of the data set is deduced from the number of points separating two consecutive results. Once the period is known, a sine function is created with the same period. It appears in Figure 9-15, plot 3. After the period is known, the position of a data point can be related to a distance to the starting point of the period, and can thus be expressed in micrometres. Each period can be isolated from the others as it corresponds to a measured circle on the gauge. To know if the period obtained by the peak finder function is the correct period, the measurements are superimposed to each other and shown to the operator. If no shift appears in the measured data the measurement period is correct, otherwise it can be corrected by the user.

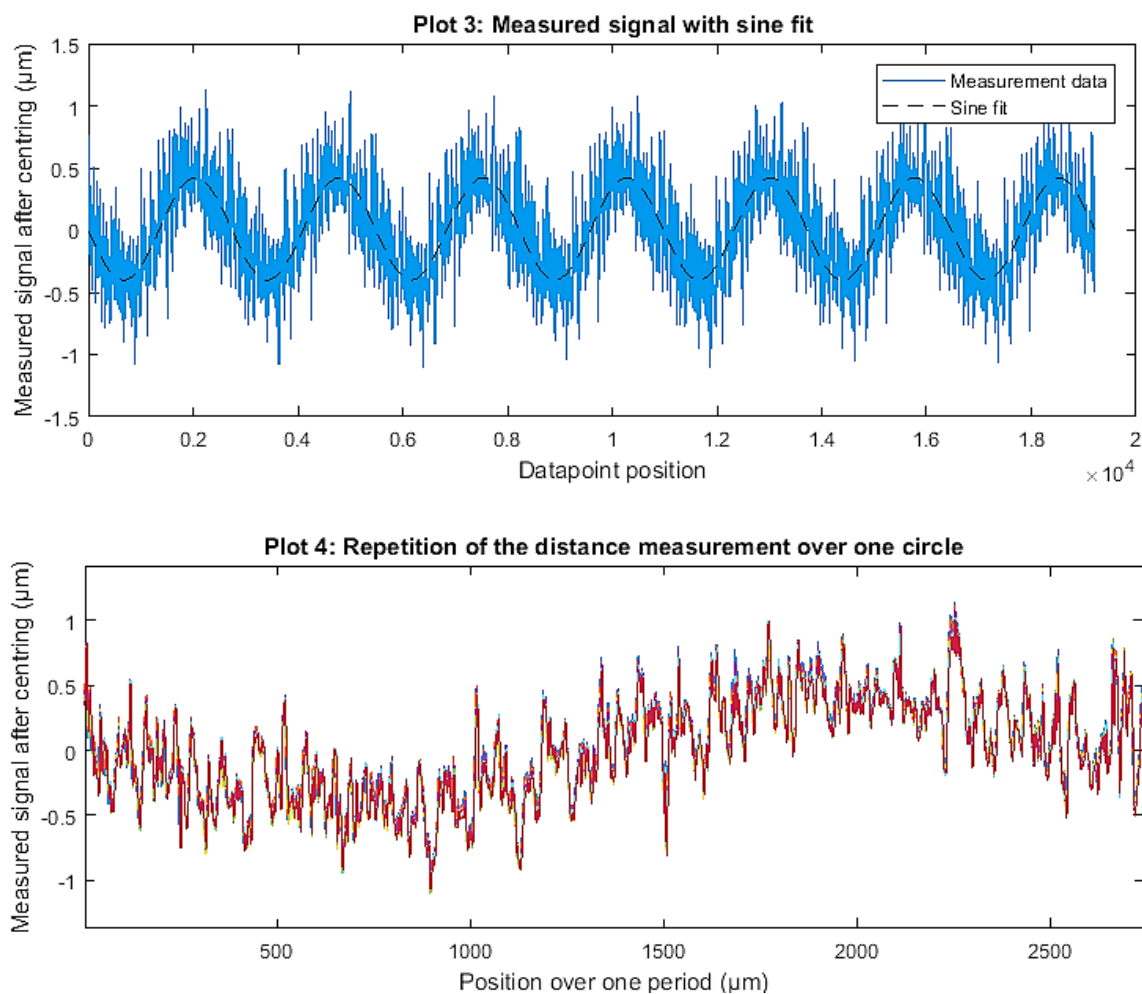
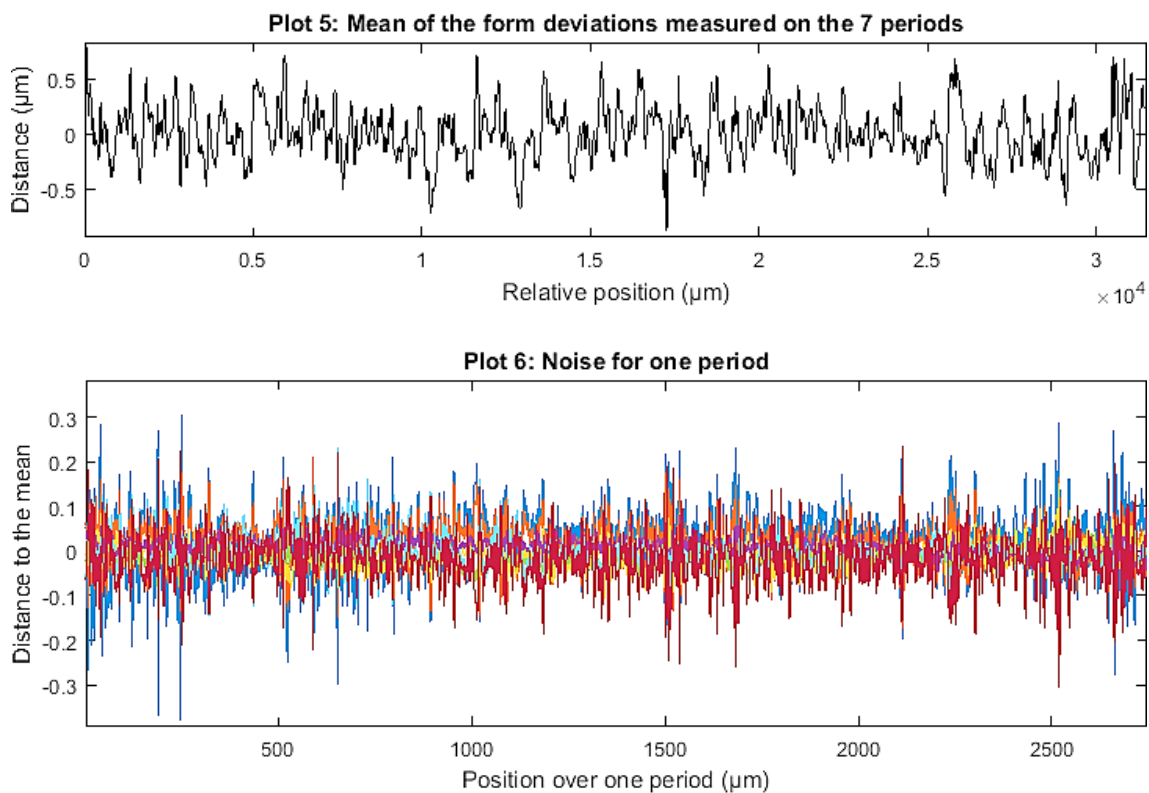


Figure 9-15: Plot 3 and plot 4 are used to validate the period found by the peak finder function

After the period is validated, the sine fit is removed from the data set. This is the equivalent of a mechanical centring of the gauge on the rotation axis of the table.

A Gauss filter with the cutting wavelength equal to the optical measurement spot diameter ($3.5\text{ }\mu\text{m}$) is applied to the data set to lower the impact of the highest spatial frequencies which should not be found in the signal. A second Gauss filter with a cutting wavelength equal to the diameter of the Hertz contact between the ruby ball and the gauge ($10\text{ }\mu\text{m}$) is applied to the data set. It is the approximation chosen to simulate the filtering effect of the contact.

The information contained in the data set at this stage is the form measurement. In order to reduce the impact of the noise on the measurement results, the measurements appearing in Figure 9-15, plot 4, are averaged. The form error is obtained from the average of the form measurements over one circle, which appears in Figure 9-16, plot 5. The noise of the dataset is defined as the difference between the measured data and the average, for each period of rotation. It is shown to the operator in plot 6, Figure 9-16, a histogram of its repartition is shown in plot 7, in the same figure. The standard deviation and Allan deviation of this noise is computed.



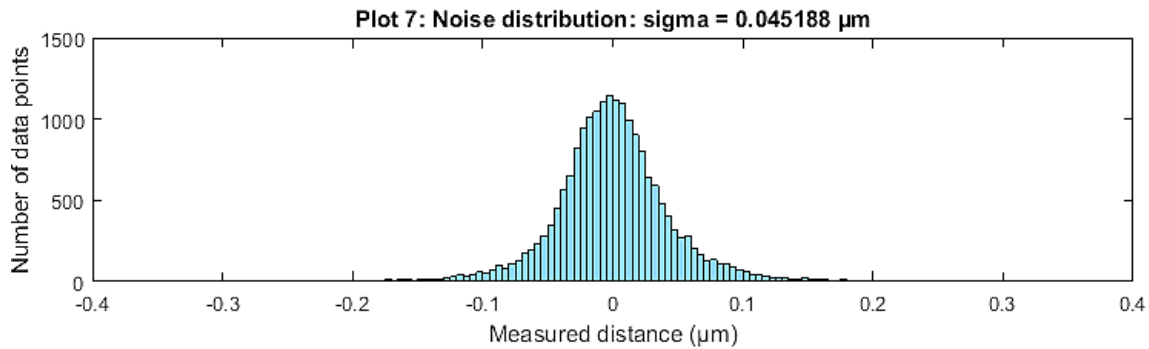


Figure 9-16: Plots giving information on the form deviation average and the random error.

If the average value of the measurements was considered as the true value for the measurement, then the noise would be the random error. In fact, it is the random error affected by some measurement bias.

The morphological filter (2.3) is applied to the averaged form measurement in order to compare it with the contacting measurements: the filtering effect of the sphere diameter on the measurement.

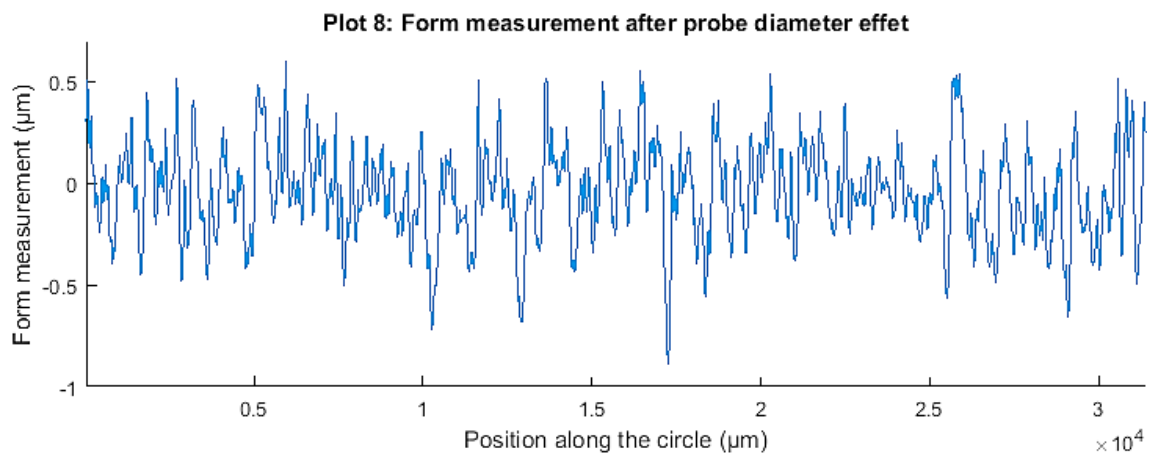


Figure 9-17: Plots

The amplitude of the measurement obtained after such filtering provides information on the form error acquired on the same sample by a contact measurement, before the normalised Gaussian filter is applied to the dataset. A Gaussian filter with 50 oscillations per round was chosen.

Measurement characteristic (unit)	Value
Noise standard deviation (nm)	45
Noise Allan deviation (nm)	12
Period (data points)	2745
Number of periods in the data set (periods)	7
Decentring of the gauge on the MarForm table (nm)	411
Form error of the optical measurement (μm)	1.71
Form error to compare with the contact measurement after 50 rpm filter (μm)	0.510

Finally, these results were compared with a traceable measurement: the contact measurement performed by the MarForm on a gauge with a diameter of 5 mm, presented in Figure 9-18. The form error obtained by the non-contact evaluation after appropriate filtering was 510 nm and the form error obtained with the MarForm traceable measurement was 226 nm. As a result, the uncertainty linked to the traceability was evaluated at 0.3 μm .

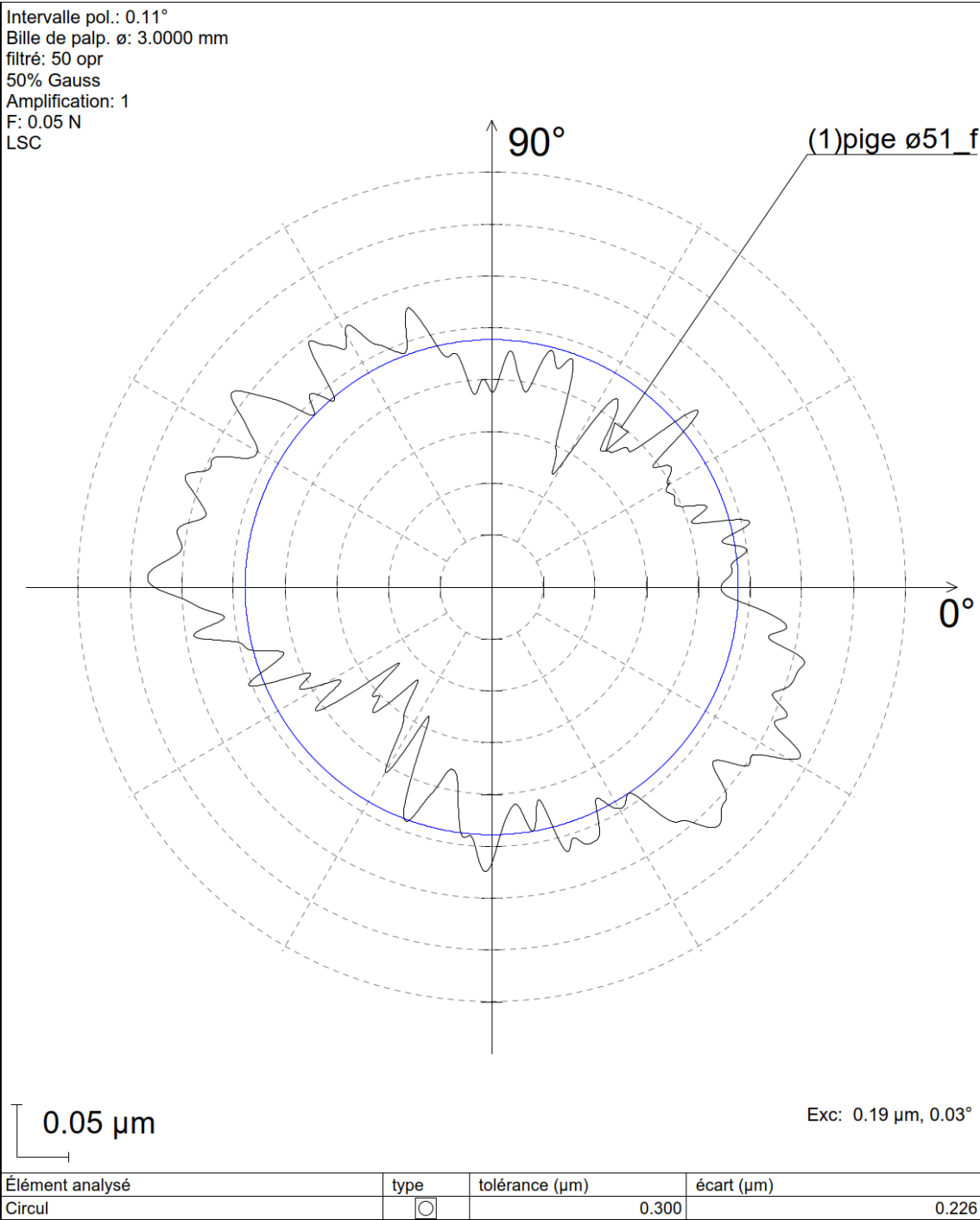
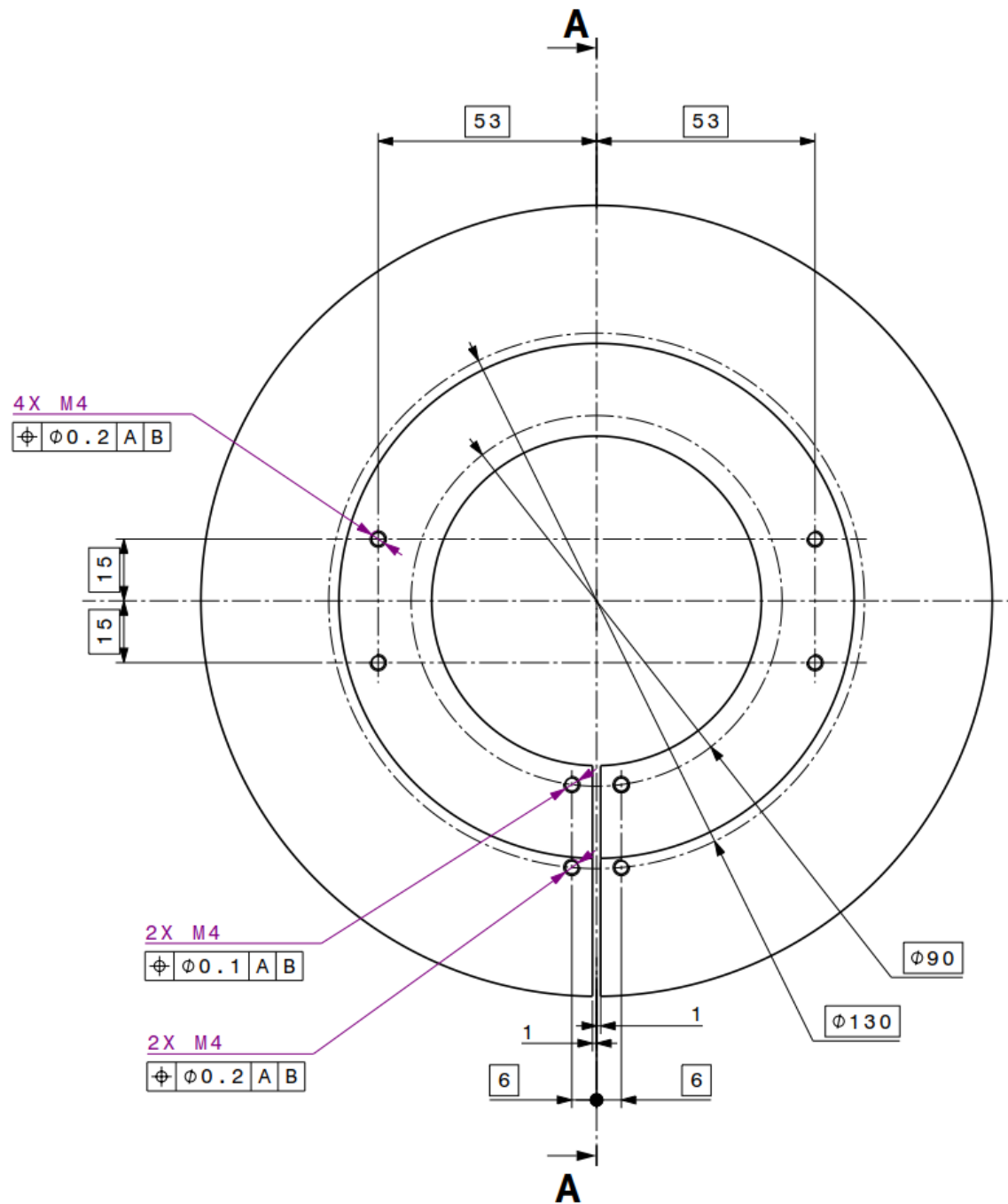


Figure 9-18: Contact form measurement result from the MarForm for a Ø 5 mm gauge

Appendix C Technical drawing extracts of SESHAT rotor

Appendix D Evaluation of the performance variation of porous air pads on discontinuous surfaces

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A new high accuracy position measurement system has been developed. It measures the position of a 0.1 mm diameter copper-beryllium wire that informs alignment of energy beams in advanced particle accelerators. This new measurement system employs air pads to provide precision and friction free rotation of a sensor. To enable the measuring system to be positioned over the wire, a slot is required in the measuring device rotor. To optimise the design of this measuring system it was necessary to understand the performance of the air pads as they pass over the gaps (slots) in the rotor. This paper describes modelling and experiments that were performed to gain understanding of air pad performance when encountering such a surface gap. Particularly, an analytical model of the variation of load of a 20 mm × 40 mm porous air pad during the passing of a 1.5 mm wide slotted surface. Subsequent experimentation revealed that although the general behaviour of the load variation had been captured effectively, a correction factor was required to correct for amplitude variations. The results of this analysis reveal that air pads of this size can reliably pass above an opening of this size with a 2% reduction in force. The results and the methodology presented in this paper can be used as an effective basis for future designs and studies.

Air bearing; Accuracy; Control

1. INTRODUCTION

One of the projects currently under development at the European Organisation for Nuclear Research (CERN) is the Compact Linear Collider (CLIC). This linear collider is being designed to accelerate electrons and positrons from two opposing directions and to focus them into an elliptical collision point of size of 1 nm × 40 nm. In order to facilitate this cross-sectional size, the incident beams need to be aligned with nanoscale precision. As a result, pre-alignment of CLIC's acceleration and focusing optics (otherwise known as elements) are required at the microscale [1].

In order to facilitate alignment of these large (several metres) devices at the micrometre level state-of-the-art measurement techniques are required. The PACMAN project (Particle Accelerator Component's Metrology and Alignment to the Nanometre scale) was launched at CERN to address this measurement need[2]. This project is based on aligning the functional axis of each of the CLIC elements with respect to external references or fiducials [3]. To perform this fiducialisation, the first steps consist of using a stretched wire to find the optimal position for the beam. Once successfully positioned, this wire represents the functional axis and facilitates high accuracy positioning using a coordinate measurement machine (CMM). The wire selected for this task has a 0.1 mm diameter and is composed of copper and beryllium.

Currently, no measurement system is capable of localising the wire with the sub-micrometric accuracy required for this application. Therefore, a new sensor, named the Shape Evaluating Sensor: High Accuracy & Touchless (SESHAT), has been designed [4].

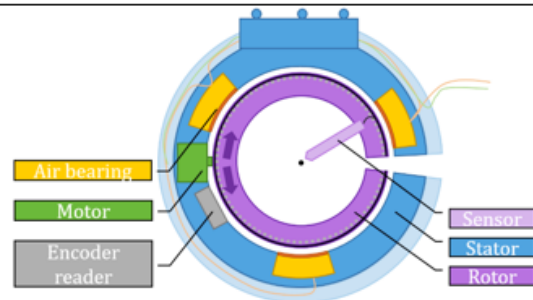


FIG. 1: Schematic of SESHAT design concept. The device is inserted across the wire (shown schematically as a black dot) through the notch, and the rotor moves rotationally relative to the stator in order to measure the form of the wire with microscale precision.

The principle of the SESHAT is to rotate a chromatic confocal sensor around the wire which appears as a black dot in FIG. 1. Air bearings are located at 3 equiangular positions around the edge of the sensor in order to suspend the rotor and facilitate rotation. At each position NewWay® [5] air bearings of two differing sizes (12×24 mm and 20×40 mm) have been employed and placed in an opposing configuration to provide necessary constraint and minimise cross torque, as shown in FIG.2. The SESHAT employs a piezoelectric actuator which is preloaded against the rotor's surface at all times with a high contact stiffness (> 50 N/μm). Additionally, the SESHAT features a notch in its rotor to allow the stretched wire to pass radially through the bearing assembly to align the sensor to the wire. The focus of this paper is to gain understanding of the influence of this rotor opening on the bearing's performance as it passes into and out of engagement with the air bearings 'active region'.

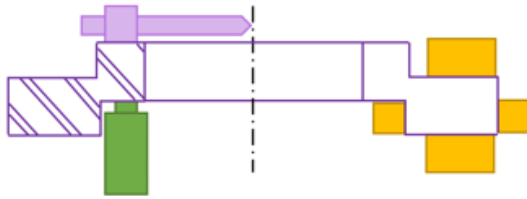


FIG. 2: Schematic drawing of the SESHAT's rotor (in purple) with its rotational axis aligned with the wire during the measurement (shown as a dashed black line). The arrangement of the sensor (in pink) which is attached to the rotor, the four air pads (in yellow) and the piezoelectric actuator (in green) are shown.

2. BACKGROUND

Air pads can provide stiff, stable, reliable, and long lasting bearings with insignificant friction [5]. These characteristics are determined by the quality of the air pads, and have been described in detail elsewhere [6]. However, their performance is also based on their assembly (the constraint of the air pad with respect to the bearing surface) and from the use of the appropriate parameters for a specific assembly. For example, the texture and profile of the bearing surface play an important role in the quality of the device. Additionally, the pressurised air must be temperature controlled to assure the bearing's stability.

Previously, the behaviour of air pads with and without porous media have been simulated and compared [7]. These studies have provided arguments both for and against the use of differing air bearing types. The application of a porous intermediate layer has been shown to be tolerable to discontinuity of the bearing surface provided that the vertical offset induced by the discontinuity is smaller than the air gap studies have also simulated the microstructure of a porous media [8] and finite element optimisation of the air pads' parameters has been performed [9]. Simplified mathematical models can also be used and have been shown to provide comparable predictions of experimental results [10].

A significant amount of research has been performed into the behaviour of air pads that are considerably larger than those required in the SESHAT design [9,11,12]. For these pads, the different air bearing parameters (stiffness, load/lift curve, etc.) have been shown to be proportional to the area over which the pad is acting. In these cases, the load bearing parameters are proportional to the average pressure of the air cushion below an air pad. However, this statement is an approximation and considered inapplicable to the small size air pads necessary for the SESHAT design.

In this paper an algebraic representation of the air pressure under an air pad with a surface area of several square millimetres is presented. This provides the pressure distribution in order to predict the stiffness evolution of an air pad as it slides across a bearing surface having a gap (slot).

Thereafter, experiments are described which validated the mathematical model as applied to the SESHAT bearings configuration. The prediction of the SESHAT performance is given based on a 1.5 mm size gap (slot). Modelling and experimental measured results are compared.

The motivation for this work has been to provide predictions of the stiffness of the SESHAT's axial 20 mm × 40 mm bearings while two of the six air pads are moving over the rotor's slot. This analysis is crucial to ensure that the stiffness of the system remains above the minimum required by the piezo drive motor at all times. It should be noted that the stiffness in the radial direction does not influence the operation SESHAT in the same manner, and therefore simulation and testing of the 12 mm × 24 mm flat air pads was not considered necessary.

3. METHOD & THEORETICAL RESULTS

3.1. Air pressure simulation model

As previously highlighted, mathematical models can be used to predict the performance of porous air pads [REF]. Previous studies have revealed that the air travelling through the pads can be modelled either by a laminar or by a turbulent flow [11]. In the present study, the air flow under consideration traverses a slot in the bearing surface and arrives at the top of the slot from two different directions: vertically from the porous media and transversally from the air cushions on each side of the air gap, as depicted in figure FIG. 3. Consequently a turbulent flow model more accurately represents the pressurised air distribution in this system.

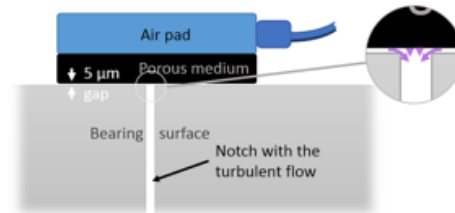


FIG. 3: Schematic side view of the air pad. The air is expelled by the porous media into the 5 µm gap between the air pad and the bearing surface. During the 'slot-passing', some air will be expelled into this channel in the bearing surface.

During the study, the question of whether the air cushion behaves in the same way when it encounters a slot in the bearing surface or one of the pad's edge arose. The answer was provided by simulations. In order to simulate the air cushion pressure at the edge of the bearing surface of the pads, the software COMSOL Multiphysics 5.2 was used. The air expelled after traversing a porous media was modelled and propagated through the air gap between the air pad and the bearing surface. This simulation was based on a turbulent flow model and a porosity value of 0.17 for the porous media was used to simulate the air pad behaviour [8].

The pressure distribution beneath the pad when the slot in the bearing surface (in black) was at the central position is shown in FIG. 4. This result demonstrates that there is no significant difference between the air pressure profile at the edge of the porous media (in grey) and that observed close to the edge of the bearing surface. Consequently, these two edge types will be considered as equivalent in the remaining computations. The profile of the air cushion obtained from the simulation result appears in FIG. 5.

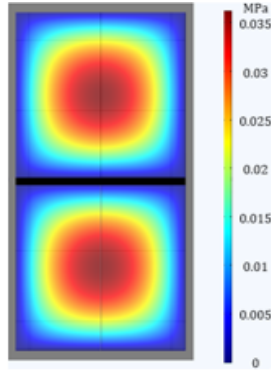


FIG. 4: Simulation result illustrating the behaviour of the air pressure under the porous media of the pad. A similar reduction in pressure is observed at the edge of the pad (grey line) and the bearing surface (black line).

3.2. Simulation of load variation above slot

The following computation evaluates the load variation of the pad as it transverses the slot in the bearing surface. In order to perform this analysis, several assumptions were made:

1. The system can be considered to be at equilibrium such that the simulation will be based on an instantaneous snapshot of the transition.
2. The stiffness of the bearing surface and air pads are infinite such that the deformations due to applied forces are negligibly small.
3. The line of action of the force on the air pad is at the centre of the air pad's length.
4. The slot is parallel to the air pad's edge, and any bevels or imperfections are neglected.
5. The variation of atmospheric air pressure around the pads is negligible such that the relative air pressure on either side of the pads is zero.
6. The dimensions of the air pads and slots are nominally correct such that the dimensional errors have a negligible influence.
7. The pad is mounted on a spherical end screw so that no friction affects its possibility of rotation.
8. The effect of the bearing surface roughness is negligible such that the model is equally applicable to all of the bearing surface.

The following analysis is based on initially obtaining a mathematical expression for the air pressure as a function of the position under the pad. This expression, in combination with the average air pressure beneath the pad (obtained from the supplier) can then be used to estimate the pressure distribution for a pad above a bearing surface with a slot.

In order to estimate the total load applied to the pad, it can be considered as two smaller pads, on each side of the resisting spherical end screw. For each of the notional pads, the force applied by the air cushion on the pad's surface can be determined by the integral of the pressure distribution over this surface. This force can be expressed as a function of the slot's

position and width, in order to provide quantitative estimates for the system.

In order to obtain a generic expression which effectively represents the air pressure under the pads, an expression based on the average pressure beneath the surface of the pad P_{Av} and the distance from the edge of the pad are required. The parameter for position is α . This variable is centered on the axis of symmetry, and is limited within the range $\pm d$ and represents a given distance from the edge of a pad. In 1D, an effective representation for the pressure P of a bearing without slot at a given point α can be written as:

$$P(\alpha) = 1.1 \times P_{Av}(1 - (\alpha/d)^{10}). \quad (1)$$

This pressure distribution equation is defined for the dimensions of a pad with P_{Av} and d parametrized using the manufacturer's data. If there is a slot reducing the bearing surface to a length λ , then x , replacing α , follows $P(\alpha)$ from zero to the half of the length of the remaining bearing surface, then it follows the same curve reversed:

$$P(x) = \begin{cases} P(\alpha), & x \in [0, \lambda/2] \\ P(d - \lambda + \alpha), & x \in [\lambda/2, \lambda] \end{cases} \quad (2)$$

This resulting pressure distribution is comparable with the simulation results outlined in Section 3.1, as shown in FIG.5, as well as those observed in previous studies [13]. It should be noted that this analysis was performed on a 12 mm $\times$ 24 mm pad, but that this is equally applicable to air pad of any size, including the 20 mm $\times$ 40 mm which is the main focus of this study.

The mathematical model was applied to an air pad with a length $d=24$ mm and a maximum pressure without slot $P_{Av} = 38.8$ kPa. Due to the slot, the bearing surface was reduced to a dimension $\lambda=12$ mm. Thus, the black curve in FIG. 5 shows the curve of equation (1) for $\alpha \in [0,6]$ – giving the pressure profile of the air cushion from an edge ($\alpha=0$ mm) to the maximum reached in this configuration (when $\alpha=\lambda/2=6$ mm).

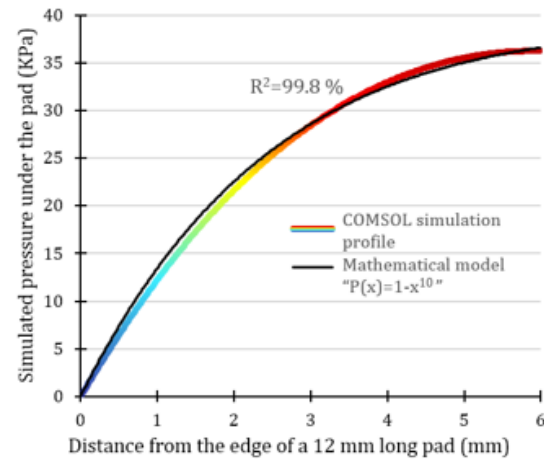


FIG. 5: Comparison between the COMSOL simulation result and proposed model, for a 12 mm long bearing surface under a 24 mm long air pad.

This parameterized expression for the variation of pressure can next be used to determine the load variation in the pad as the slot passes beneath the surface. For sake of analysis, the total width of the pad will be written as w and the total length as l . The pad can be considered in two halves: one to the left of the spherical end screw appearing in pink in FIG. 6 and one to its right. The pressure distribution can also be considered as two distinct regions: P_I is to the left of the slot (over a distance of $0.5l + s_1$) while P_{II} is to the right of the slot (over a distance $0.5l - s_2$) as shown in FIG. 6 (where the slot appears in red).

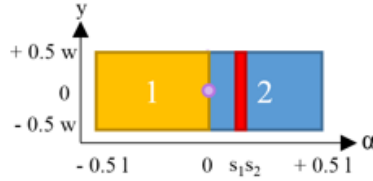


FIG. 6: Top view. The bearing surface of width w and length l is shown separated into two parts (1 in yellow and 2 in blue). The red region represents the slot which has a thickness of s_1-s_2 . The position of the spherical end screw is shown in pink.

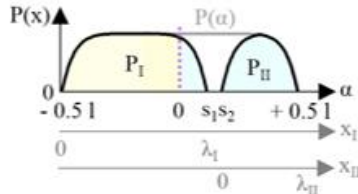


FIG. 7: The pressure distributions P_I and P_{II} are identified. The integral P_I is shown in light yellow and P_{II} in light blue, on each side of the pad's middle (shown as a purple dashed line).

The total load lift from the pad, F_T , is resisted by the spherical end screw and is equal to the sum of the forces generated by the two sides of the pad (F_{P1} and F_{P2}). For each side, the total reaction force is equal to the integral of the pressure distribution $P(x, y)$ over the cross sectional area (A) of the side:

$$\iint_A P(x, y) \cdot dA. \quad (3)$$

The expression for $P(x, y)$ can be obtained using 2D formulation of equation (1). Substituting values for the limits in the coordinates x and y shown in FIG. 6, gives the following expressions for the forces of the two sides as a function of the slot position s :

$$F_1(s) = \int_{-0.5l}^0 \int_{-0.5w}^{0.5w} P_I(x_I, y_I) \cdot dy_I \cdot dx_I, \quad (4)$$

$$F_2(s) = \int_0^{s_1} \int_{-0.5w}^{0.5w} P_I(x_I, y_I) \cdot dy_I \cdot dx_I + \int_{s_2}^{0.5l} \int_{-0.5w}^{0.5w} P_{II}(x_{II}, y_{II}) \cdot dy_{II} \cdot dx_{II}, \quad (5)$$

where the subscripts 1 and 2 of the forces refer to the sides 1 and 2. It can be seen that since the width of the pad is constant, the influence of the pressure distribution in the y direction can

be considered to be constant and an approximation factor k compensating for the integral along y can be used. The force can then be computed using the following expressions which were implemented within a MATLAB function:

$$F_1(s) = k \int_{-0.5l}^0 P_I(x_I) \cdot dx_I, \quad (6)$$

$$F_2(s) = k \left(\int_0^{s_1} P_I(x_I) \cdot dx_I + \int_{s_2}^{0.5l} P_{II}(x_{II}) \cdot dx_{II} \right) \quad (7)$$

The differences between pads may induce a different reaction force for an identical pressure profile. This relationship is dependent upon the dimensions of the pad and the vertical offset between the pad and the mounting surface, which varies with the stiffness. Consequently a final correction factor ϵ , needs to be determined experimentally in order to determine the final load F_F :

$$F_F = 1 - \epsilon * (1 - F_T) \quad (8)$$

3.3. Test bench configuration

In order to validate the model, experimental tests were performed. A 20 mm × 40 mm air pad was arranged to slide in a direction perpendicular to a lapped part which contained a 1.5 mm wide slot. During this process the load generated by the pad was measured.

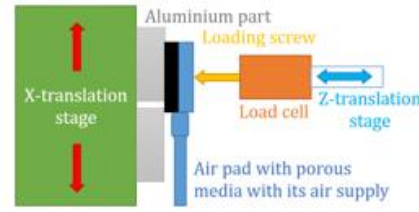


FIG. 8: Schematic of the test bench principle (top view)

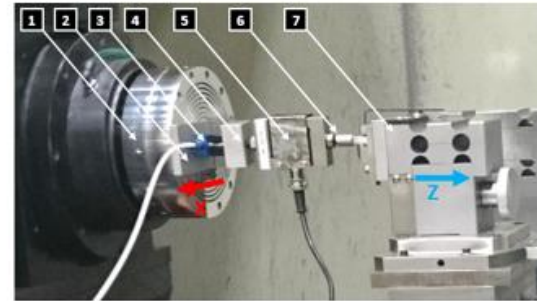


FIG. 9: Overview of the test bench showing key components. (1) The X translation stage of the turning machine (perpendicular to Z, toward the camera that shot the photo). (2) An aluminium plate containing the 1.5 mm slot which was held onto the translation stage by vacuum. (3) The air pad under test. (4) Adapter between the load cell and air pad loading spherical end screw. (5) The load cell. (6) A screw tightening the load cell and fitting with the machine's holding system. (7) The Z translation stage of the turning machine.

The test bench (see FIG. 8 & FIG. 9) was composed of different elements:

- The 20 mm × 40 mm air pad being tested with a temperature controlled (to ± 0.5 °C) air input.
- An aluminium plate featuring a 4 mm deep and 1.5 mm large slot. The two sides were aligned to be parallel, and were produced using lapping to produce a surface with a flatness of 2 µm and a roughness Ra of 0.4 µm.
- A Moore Nanotech 350 UPL turning machine which was used for both pre-alignment and load control at nanoscale precision.
- A Maywoods Instruments U4000 load cell powered by a BST PSA30/3B power supply and read by a Keithley 175 multimeter. The resolution of this setup was 10 µV over a range of 4 mV. Calibration was performed across the expected loading range (0 to 11.5 kg) using a set of known weights prior to the experiment.

The two principal movements used in this experiment are the lathe's X and Z linear axes; the Z axis can be used to change the load applied by the air pad, and the X axis can be used to change the relative position of the slot with respect to the air bearing pad. The high stiffness of the precision turning machine minimises errors of the measurement. The vacuum holder was used to secure the aluminium plate during the experiment.

4. PRACTICAL RESULTS: MODEL VALIDATION

4.1. System calibration

Evaluation of the test setup was performed by reproducing the load/lift curve and stiffness curves for the air pad of interest. These curves are provided by the manufacturer [5] for larger air pads, however only one nominal data point had been given for the small air pads used in the SESHAT. In order to populate these curves, the load applied by the pad was incrementally adjusted from 22 N to 169 N (1 mV to 4.5 mV) in 16.3 N steps (0.5 mV). Each air gap was evaluated following several steps:

- 1) a given force F was applied to the air pad without air from the air supply,
- 2) the readout of the Z-axis was recorded,
- 3) the air supply was switched on,
- 4) the machine was translated along its Z-axis until the same force F was applied to the air pad,
- 5) the readout of the Z-axis was recorded again,
- 6) the change in the Z axis readout was used to approximate the air gap induced by the pad.

The measurement was performed between one and four times for a given load, as show in FIG. 10.

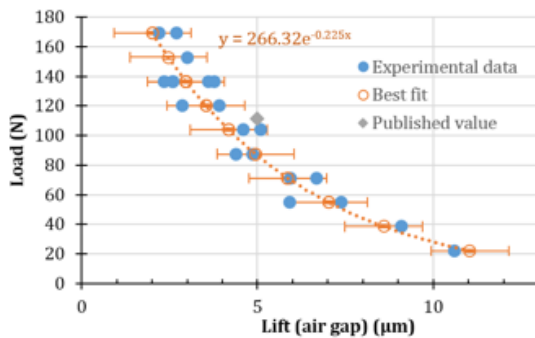


FIG. 10: Lift/Load curve obtained from the 20 mm × 40 mm porous air bearing. The error bars demonstrate the uncertainty of each of the best fit values, which have 99.7% confidence intervals of ±1 N and ±1.1 µm, for the load and air gap, respectively.

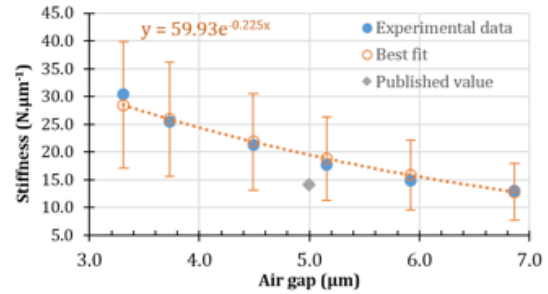


FIG. 11: Stiffness as a function of the air gap for the 20 mm × 40 mm porous air pad. The error bars are derived from those obtained in the lift/load curve.

In order to obtain stiffness estimates s , the load / lift results were differentiated by dividing the change in force by the change in the air gap distance:

$$s(a_n) = \frac{F(a_{n+1}) - F(a_n)}{a_{n+1} - a_n}, \quad (9)$$

where a_n is the air gap thickness at a specific position n and a_{n+1} is the subsequent thickness estimate. Both the stiffness and force F are deemed to be functions of the air gap thickness. [this needs explaining!]

An identical mathematical treatment to produce the line of best fit in FIG.10 was performed to obtain the equivalent line given in FIG. 11. Propagation of the error bars was also performed using a similar approach.

4.2. Force variation with pad position

Force variation testing was performed by moving the slot from one end of the air bearing pad to the other end in 1 mm steps. At each position, the force measured by the load cell was logged. This measurement was repeated 6 times, and with two nominally identical air pads. The two air pads data can be observed in FIG. 12.

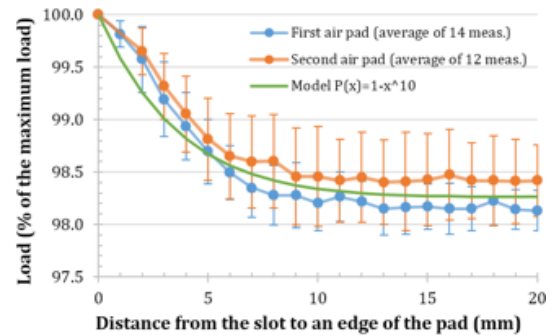


FIG. 12: Static load of a 20 × 40 mm² air pad as a function of the position of a 1.5 mm large slot sliding below the pad, along its length. The results are expressed as percentages of the maximum load and the errors bars show the 67% confidence intervals.

The tests were performed in a temperature controlled room with a nominal at $20\text{ }^{\circ}\text{C} \pm 0.5\text{ }^{\circ}\text{C}$. Nevertheless, a load variation of 1 % was seen in the repeatability measurements, which was most likely associated with thermal effects. To minimise this effect, the measurements were performed as fast as possible.

Subsequent to the experimental tests the porous graphite air bearing pad surface was inspected and shown not to be damaged. The model was adjusted to the measurement data using $\epsilon=0.08$.

5. DISCUSSION

In this report a new analytical model is presented to simulate the response of porous media air pads when the opposing surface contains a slot. Comparison of its results with experimental data has demonstrated this model captures well the behaviour of the pad. However, despite the quality of the correlation, individual data points were found to be noisy in the experimental data set. This noise was associated with the test bench setup. A number of enhancements for future testing include:

- A loading spherical end screw could be machined in order to make direct contact with the load cell, thereby reducing the number of interfaces and increasing the mechanical stiffness of the system.
- An automated voltage measurement routine should be implemented to reduce the time to perform measurements. This would reduce the error by facilitating faster measurement protocols and reducing thermal influences and enabling dynamic measurements to be performed.
- An independent displacement sensor should be applied to directly record the air gap, rather than relying on the displacement recorded by the diamond turning machines motions. This will reduce the impact of the error associated with these two measurements.
- The resolution of the load cell (currently 0.4 N), should be improved to enhance the results.

The need for the factor ϵ is easily explicable: the model provided considers the air gap as a constant. In fact, as it slides above the opening, the stiffness of the pad is reduced. This engenders a decrease of the air gap that leads to an increase in the stiffness and load capacity (following a curve similar to the lift/load curve), thus reducing the impact of the slot on the load capacity. An additional limitation is the measurement system which has its own stiffness reducing the measured load variation.

The shape of the modelled curve does not match exactly the experimental data in FIG. 12. This may be explained by the surface of the spherical end screw resisting the air pad: the spherical end screw has a spherical extremity with a surface roughness which slightly resists the angular motion. The influence induced by this resistance on the moment is larger when the slot approaches the position of the spherical end screw because of the reduced lever arm.

Further research on how the stiffness of an air pad is affected by an opening could lead to the self-calibration of the model. This would allow for a generalisation of this model, which would

predict load variation for any type of opening in the bearing surface.

6. CONCLUSIONS

A number of different conclusions can be drawn from the results obtained in this article. The first, and perhaps most important is that as stated in their manufacturer's datasheet [5], 20 mm $\times$ 40 mm air pads using state of the art porous graphite media, can be reliably used above an opening without being damaged.

A model of the load reduction on an air pad while passing a linear opening has been presented and experimentally validated in this paper. The pressure distributions and integration presented has potential for use in a broad range of air pad designs, however calibration of manufacturer specific correction factors are still necessary to make use of this approach. Additionally the lift/load and stiffness curves for NewWay 20 mm $\times$ 40 mm air pad with porous media is provided.

Concerning the SESHAT design project, the provided model shows that the load variation is not larger than 2 %. This means that the stiffness variation of the air pad/air cushion assembly is self-compensating and that the required stiffness remains above the required 50 N/ μm at all times. Further simulations will be performed using the results of this analysis in order to determine the impact on the results of the high precision measurement system.

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Appendix E Terminology used in this thesis

This appendix introduces the terms and concepts used throughout this thesis. The vocabulary definitions are quoted from the following sources:

- International Vocabulary of Metrology, known as VIM (BIPM, 2008)
- ISO 10360: Acceptance and reverification tests for Coordinate Measuring Machines (ISO, 2001b)
- ISO 12180: Cylindricity (ISO, 2011b)
- ISO 12181: Roundness (ISO, 2011c)
- ISO 12781: Flatness(ISO, 2011d)
- Guide to the expression of Uncertainty in Measurement, known as GUM (JCGM, 2008a)
- Measurement Uncertainty Analysis Principle and Methods (NASA, 2010): a handbook written by the National Aeronautics and Space Administration
- Merriam-Webster online dictionary

E.1 Accuracy

“Accuracy is the closeness of agreement between a measured quantity value and a true quantity value of a measurand” (BIPM, 2008)

E.2 Calibration

“Operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication” (BIPM, 2008)

E.3 Contacting probing system

“Probing system which needs material contact with a surface being measured in order to function” (ISO, 2001b)

E.4 Comparability

“Metrological comparability of measurement results, for quantities of a given kind, that are metrologically traceable to the same reference” (BIPM, 2008)

E.5 Coordinate Measuring Machine CMM

“Measuring system with the means to move a probing system and capability to determine spatial coordinates on a workpiece surface” (ISO, 2001b)

E.6 Cylindricity

Cylindricity: “Property of a cylinder” (ISO, 2011b)

Peak-to-valley cylindricity deviation: “Value of the largest positive local cylindricity deviation added to the absolute value of the largest negative local cylindricity deviation” (ISO, 2011b)

In this thesis, the terminology ‘cylindricity’ is used to refer to the peak-to-valley cylindricity deviation defined for a least squares reference cylinder (E.8).

E.7 Deviation: cylindricity/flatness/roundness deviation

“Deviation of a point, on a digital representation of the real surface intentionally modified by a filter, from the reference *cylinder/plane/circle*, the deviation being normal to the reference *cylinder/plane/circle*.”(ISO, 2011b, 2011d, 2011c)

E.8 Flatness

Flatness: “Property of a plane”

Peak-to-valley flatness deviation: “Value of the largest positive local flatness deviation added to the absolute value of the largest negative local flatness deviation” (ISO, 2011d)

In this thesis, the terminology ‘flatness’ is used to refer to the peak-to-valley flatness deviation defined for a least squares reference cylinder (E.8).

E.9 Least squares reference *cylinder/plane/circle*

“*Cylinder/plane/circle* such that the sum of the squares of the local *cylindricity/flatness/roundness* deviations is minimum” (ISO, 2011b, 2011d, 2011c)(CEN, 2011b)(CEN, 2011a)

E.10 Lever arm

“The lever arm is the perpendicular distance from the fulcrum of a lever to the line of action of the effort or to the line of action of the mass.” (Merriam-Webster, n.d.)

E.11 Maximum Permissible Error of indication of a CMM for size measurement MPE_E

“Extreme value of the error of indication of a CMM for size measurement permitted by specification, regulation etc. for a CMM” (ISO, 2001b)

E.12 Measurand

“Quantity intended to be measured” (BIPM, 2008)

E.13 Measurement

“Process of experimentally obtaining one or more quantity values that can reasonably be attributed to a quantity” (BIPM, 2008)

E.14 Measuring volume

“Measuring range of a CMM, stated as simultaneous limits on all spatial coordinates measured by a CMM” (ISO, 2001b)

E.15 Metrology

“Science of measurement and its application” (BIPM, 2008)

E.16 Nominal *cylinder*

“Mathematically *cylindrical* form as specified by design content” (ISO, 2011b)

E.17 Non-contacting probing system

“Probing system which needs no material contact with a surface being measured in order to function” (ISO, 2001b)

E.18 Precision

“Measurement precision is the closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions” (BIPM, 2008)

E.19 Probe

“Device that generates the signal during probing” (ISO, 2001b)

E.20 Probing (noun) – to probe (verb)

“Action which results in the determination of coordinate values” (ISO, 2001b)

E.21 Range

“Difference between the greatest and the smallest value of nominally the same quantity” (ISO, 2001b)

E.22 Repeatability

“Repeatability condition of measurement is the condition of measurement, out of a set of conditions that includes the same measurement procedure, same operators, same measuring system, same operating conditions and same location and replicate measurements on the same or similar objects over a short period of time” (BIPM, 2008)

The expression ‘repeatability measurement’ refers to measurements performed in the respect of the repeatability conditions of measurement.

E.23 Rotary table

“Workpiece mounting device which rotates a workpiece with respect to the linear motion axes of a CMM” (ISO, 2001b)

E.24 Roundness

Roundness: “Property of a circle”

Peak-to-valley roundness deviation: “Value of the largest positive local roundness deviation added to the absolute value of the largest negative local roundness deviation” (ISO, 2011c)

In this thesis, the terminology ‘roundness’ is used to refer to the peak-to-valley roundness deviation defined for a least squares reference circle (E.8).

E.25 Rule of thumb concerning uncertainty in measurement

A rule of thumb in metrology is that the uncertainty for a measurement system is usually 5 to 10 times smaller than the number given for the tolerance on the characteristic to be measured (Swyt, 2001).

E.26 Tip: Stylus tip

“Physical element that establishes the contact with the workpiece” (ISO, 2001b)

E.27 Traceability

“Metrological traceability property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty.” (BIPM, 2008)