Mini-CAS - Course on Mechanical and Materials Engineering for Accelerators, 6.11.20-22.01.21

METROLOGY

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EN/MME-MM, CERN - 27th November 2020

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Outline

1. History of Metrology
2. Introduction to Metrology
3. Metrology equipment
4. Approach to CMM measurement
5. Examples
History of Metrology

• Up to French Revolution, arbitrary standards based on:
  • Local kings or governors such:
    • foot,
    • inch,
    • line: $1/12^{th}$ of inch,
    • Journal
    • Pint.

• Non decimal System ($12^{th}$, $60^{th}$, $64^{th}$…)

• But... How to do to understand?
  • Germany: 19 different feet,
  • Europe: 18 others.

Trade and exchanges were difficult, and abuse and scams were frequent
After the French revolution, the French scientists began to work quickly and define the meter.

In March 1790, he proposes a System of Unification of the Measurements.
The idea of the meter is:
- Universal unit
- Not linked to a person

The meter, from Greek "metron" Which means measurement

On the 26th of March 1791 define the meter as 1/10 000 000 part of the quarter of the meridian of the earth.
Evolution of the definition of the Meter

1791
1796
1797
1889
1960
1983

1/10 000 000 part of the quarter of the meridian of the earth.

Fabrication of 10 standards of the meter in Paris

The bars were to be made of a special alloy, 90% platinum and 10% iridium, have a special X-shaped cross section used as an international standard.

The 11th General Conference on Weights and Measures (CGPM) redefine the meter as a length equal to 1 650 763.73 wavelengths in vacuum of the radiation corresponding to the transition between the levels 2p10 and 5d5 of the krypton 86 atom.

The 17th CGPM redefine the meter is the length of the path travelled by light in vacuum during a time interval of 1/299,792,458 of a second.
What is the point of measuring?

- Quantify the physical quantities
- Help for decision (conform, non conform, dangerous ...)

**False or erroneous results could lead to serious consequences**

- Hence the need for reliable results
  - Reliable result minimizes the risk of measurement errors and their consequences

- Reliable results can be obtained by the whole process analysis
  - A fishbone (ISHIKAWA) diagram could help
Measurement process

- The measurement can be done:
  - With **measurement instrument**
  - Or with a measurement machine.

- **By comparison**:
  - Length: a graduated ruler,
  - Angles: an angle protractor,
  - Mass: a balance with masses

- **By transformation** of a physical phenomenon by an electric current.

Most of modern devices work on this principle

This gives a number or numbers
Types de Metrology

• Separated in 3 categories
  • Fundamental or scientific metrology
  • Industrial metrology
  • Legal metrology
In 1997 the Joint Committee for Guides in Metrology (JCGM) : *International vocabulary of metrology — Basic and general concepts and associated terms (VIM)*
Norms

- ISO 1 - Standard reference temperature for geometrical product specification and verification
- ISO 286 - System of limits and fits
- ISO 5458 - Positional tolerancing
- ISO 5459 - Geometrical tolerancing
- ISO 2692 - Maximum material requirement (MMR), least material requirement (LMR) and reciprocity requirement (RPR)
- ISO 10579 - Dimensioning and tolerancing -- Non-rigid parts
- ISO 8015 - Fundamentals -- Concepts, principles and rules
- ISO 1101 - Geometrical tolerancing -- Tolerances of form, orientation, location and run-out
- ISO 10578 - Tolerancing of orientation and location -- Projected tolerance zone
- ISO 3040 - Dimensioning and tolerancing -- Cones
- ISO 1302 - Geometrical Product Specifications (GPS) -- Indication of surface texture in technical product documentation
- ISO 2768 - General tolerances
- ISO 13715 - Edges of undefined shape

... and many others
ISO 1 - Standard Reference Temperature

- ISO 1 is a standard for the specification of the reference temperature for geometrical product specification. The temperature was set to 20°C, which is equal to 293.15 kelvins and 68 degrees Fahrenheit.
- All the measurements should be made or converted to 20°C in order to get rid of thermal expansion.
- The reference temperature of 20°C was adopted by the CIPM in 1931... as 20°C = 68°F.

### Linear CTE (x 10^-6 K^-1)

<table>
<thead>
<tr>
<th>Material</th>
<th>Linear CTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>24</td>
</tr>
<tr>
<td>Copper</td>
<td>17</td>
</tr>
<tr>
<td>Austenitic Stainless steel</td>
<td>16</td>
</tr>
<tr>
<td>Steel</td>
<td>10.8 to 13</td>
</tr>
<tr>
<td>Silicon</td>
<td>2.56</td>
</tr>
<tr>
<td>Invar</td>
<td>1.2</td>
</tr>
<tr>
<td>Glass-ceramic (Zerodur®)</td>
<td>0.01 - 0.02</td>
</tr>
</tbody>
</table>

45 mm for the LHC Cold Mass of 15 meters
ISO 1101 - (GPS) Geometrical Product Specifications

- Form
- Orientation
- Location
- Run-out
Technical drawings

Value with specific tolerance

Value without specific tolerance

Additional symbol

Thread

Text

Mini-CAS Mechanical and Materials Engineering for Accelerators

General tolerances

System of limits and fits tolerances

Roughness

Geometrical tolerances

Theoretical value

Angle

Thread A-A

Orientation indifférente

Text

Value with specific tolerance

Value without specific tolerance

Additional symbol

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Text
Dimensioning and tolerancing

Geometric model of a part form the design office

- The part is considered as **elementary surfaces**.

**Dimensioning**: To define, by a 2D drawing or a 3D CAD, the shape, the size, the position with respect to other surfaces of all the elementary surfaces of the part.

**Tolerancing**: To define, with tolerances, the maximum deviations of the reel surfaces with respect to theoretical surfaces (perfect surfaces).
Traceability – Chain of measurements
Measurement uncertainty

- The GUM (Guide to the Expression of Uncertainty in Measurement) defines measurement uncertainty as a "parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand"

- Measurement ≠ true value
- Deviations are called errors
- 2 sources of errors:
  - Random errors
  - Systematic errors

\[ L = 321.32 \pm 0.05 \text{ mm} \]
Accuracy vs Precision

**Accuracy**
How close are the measurements to the true value.

**Precision**
How reproducible are the measurements?

- Both Accurate and Precise
- Accurate, but not Precise
- Precise, but not Accurate
- Neither Accurate nor Precise
Dimensional measurement at CERN

**METROLOGY**

- ± 0.0003 mm
- ± 0.010 mm
- ± 0.100 mm

**SURVEY**

- ± 0.1 mm
- ± 0.2 mm
- ...
Metrology Equipment Overview

- Conventional measurement instruments
- CMMs (Coordinate Measuring Machines)
- Portable CMMs
  - Polyarticulated arm
  - 3D Scanner
- Contact profiles and roughness devices
- Non contact topography and roughness devices
- Form and shape measurement devices
- Interferometry
- Tomography...
CMM (Coordinate Measuring Machine)

- Architecture of CMMs
CMM (Coordinate Measuring Machine)

- Architecture of CMMs
- Operation
  - Air bearings
CMM (Coordinate Measuring Machine)

- Architecture of CMMs
- Operation
  - Air bearings
  - Scales bars

Scale pitch 20 µm
Thermal expansion 0.02 µm/m/K
CMM (Coordinate Measuring Machine) Measurement head

- Architecture of CMMs

<table>
<thead>
<tr>
<th>SCANNING HEADS</th>
<th>POINT BY POINT TRIGGER HEAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEFORMABLE PARALLELOGRAM</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FIXED HEADS</th>
<th>ROTATIVE HEADS</th>
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</thead>
</table>

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CMM (Coordinate Measuring Machine)
Measurement head

SCANNING HEADS
DEFORMABLE PARALLELOGRAM

Dynamic Single-Point Probing

Deflection vs. Time

Move-in
Retract
Measuring
CMM (Coordinate Measuring Machine) Measurement head

- Architecture of CMMs
- Operation
CMM (Coordinate Measuring Machine)  
Stylus calibration
CMM (Coordinate Measuring Machine) Metrology software
CLIC – Compact Linear Collider
Leitz PMM-C Infinity

Measuring room

Airlock

Some References

- Modus, USA
- Sandia, USA
- Nano Precision Products, USA
- Bosch, Germany

Measuring room specifications:

- Temperature: 0.1 K / Meter, 0.2 K / Hour, 0.4 K / Day
- Humidity: 50% ± 5%

Accuracy (according to ISO 10360):

- MPE_E = 0.3 + L/1000 µm
- MPE_P = 0.4 µm
- THP = 1.2 µm / 59s

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Mini-CAS Mechanical and Materials Engineering for Accelerators
Leitz PMM-C Infinity

- LHC b RICH1
- Spherical mirror
- PRECITEC LR
- Optical sensor
- LINAC 4
- Chopper/dump
- CLIC Disks
Equipment

C-Track

HandyPROBE

MetraSCAN
METRASCAN CREAFORM 3D SCANNER

Beam Screen

• Final focalization Magnets
• Called Inner triplet
• New Inner Triplet for the focalization of the beam around ATLAS and CMS experiments
• New Beam Screens

• EN/MME in collaboration with BE department
• Production of 51 beam screens in total
• About 650 m including spares
• Segments number : 227
• Segment length : 2800 mm
• Length welded BS : up to 14 m
1. Measure the geometry of the beam screen (BS)
2. Straightness after welding of the segments
3. Guarantee the entrance of the assembled BS in the cold bore tube
4. Control the aperture for the beam
CRAB CAVITIES DQW & RFD
Double Quarter Wave & Radio Frequency Dipole
CRAB CAVITIES DQW & RFD

Complex process...

- Design
- FEM calculations
- Magnetic simulations
- Vacuum
- Cryogenics
- Radio Frequency
- Metrology
- Alignment
- Mechanical test
- ...

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CRAB CAVITIES DQW & RFD

Few key parts
CRAB CAVITIES DQW & RFD
TOMOGRAPH

Microfocus X-Ray system

ZEISS METROTOM 1500
Delivered
December 2017

- FDD: 1500 mm
- Max. voltage ≥225 kV, max.
- Focal spot size ≤7 µm;
- Imager: 2048 x 2048 pixels,
- Max. pixel size: 200 µm,
- Image processing: 16-bit;
65,535 grey levels
Micro Tomography

METROLOGY APPLICATIONS
Follow up of all the fabrications steps
- Tolerances ±0.005 mm was obtained
- Verification of each part after machining process
- Check if before and after brazing
- Final check to confirm the results obtained by the radio frequency tests

HF-RFQ – PROTON THERAPY
CMM : Prismo Ultra

ZEISS PRISMO ULTRA

Measuring Range

<table>
<thead>
<tr>
<th>Date</th>
<th>Measuring Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.12.10</td>
<td>1800 x 1200 x 1000 mm³ (RT)</td>
</tr>
<tr>
<td>24.12.10</td>
<td>2400 x 1200 x 1000 mm³</td>
</tr>
</tbody>
</table>

Accuracy (according to ISO 10360)

<table>
<thead>
<tr>
<th>MPE</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>E0</td>
<td>1.2 + L/500 µm</td>
</tr>
<tr>
<td>R0</td>
<td>0.8 µm</td>
</tr>
<tr>
<td>THP</td>
<td>1.2 µm / 45s</td>
</tr>
</tbody>
</table>

With Rotary Table (RT)
Thank you for your attention

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