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Traceability of In-Process Measurement of Workpiece Geometry

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Abstract

In-process metrology is applied in industrial processes with the aim of obtaining and analysing quality data directly in the manufacturing process. An effective approach for improving the manufacturing processes is the incorporation of traceable dimensional metrology directly on machine tools. European project EMRP IND62 TIM that was agreed between EC and European metrology association Euramet is aimed to introduce a traceability chain into in-process geometrical measurements. One of the tasks of the project is to develop highly accurate robust temperature invariant measurement standards that can be used in the harsh environment of the production floor for verification and mapping of the measurement errors of machine tools. Laboratory for Production measurement (LTM) at the University of Maribor - Faculty of Mechanical Engineering is taking part in the consortium of this joint research project. The main task of LTM is to develop, manufacture and calibrate at least 1D measurement standard with length up to 2 m and with thermal expansion coefficient close to 0. The task will be performed in co-operation with EMO Orodjarna, Gorenje Orodjarana and Veplas. The design is based on composite body and ceramic probing balls. Original approach of compensating thermal expansion was introduced in order to enable use of the standard in harsh environmental conditions. The article presents basic principles of in-process measurement traceability as well as the physical standard under development and application possibilities of this standard.

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Keywords: Traceability; production process; calibration; measurement standard; machine-tool capability

1. Introduction

Metrological traceability is a 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 [1]. It

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requires an established calibration hierarchy. Measurement traceability is founded on the national standards, which are provided to the industrial end-users by national metrology institutes (NMIs). Achieving traceable and reliable dimensional measurements on the shop floor requires the standards that are deployable on machine tools to be robust and non-susceptible to the environmental conditions on the manufacturing floor. Control of thermo-mechanical errors on the machine tool is not the responsibility of the machine tool manufacturers alone. Machine tool end-users require qualified and calibrated standards and procedures to guide them to mitigate, control and correct the errors. Only well controlled machine tool allows reliable optimisation of machining parameters [2,3]. At the time, neither the machine tool manufacturers nor the end-users have the required stable standards to do the corrections in real-life machining conditions. Furthermore, existing standards for machine calibration do not adequately address the environmental conditions on the shop floor. Therefore there is an urgent need for a new generation of robust material standards with corresponding procedures and guidelines for the assessment of machine tool measurement performance directly on the shop floor [4].

2. Novel approaches of assuring traceability of in-process measurements

Modern approaches of assuring traceability of in-process measurements shall deliver standards and procedures for ensuring the improvement of measurement accuracy and reliability of in-process measurements. European project EMRP IND62 TIM will deliver robust and thermal invariant multi-purpose material standards and a mobile simulator which will emulate shop floor environmental conditions. It will also offer procedures that enhance the characterisation and compensation of the dimensional measurement errors of machine tools and integrated measurement devices [4].

Three quarters of all geometrical errors [5,6] on machined workpieces are induced by the effect of temperature variations within the machine. Although a number of procedures exist to measure thermally induced displacements and deformations of individual machine tool components [7], it is extremely difficult to predict their cumulative impact on the wide range of different workpieces and on their large variety of shapes. To overcome this difficulty with measurements on machine tools, highly accurate, thermo-invariant multi-purpose material standards will be developed. These will quantify the influence of temperature and their variations on a series of different shapes and form measurement tasks in order to determine systematic measurement errors and to derive measurement uncertainties.

3. Material standard for verifying metrological performance of machine-tools

The standard is aimed for checking geometrical properties of machining centres with various production volumes (up to 3 m per axis) and various numbers of axes [5,6]. The metrological check will be performed with no load. As a result, metrological check will return machine tool compliance with specification (MPEs). No error mapping like in some other traceability approaches is expected to be performed by using the metrological results. The machining centre under test shall be equipped with a tactile probing system attached on the machine (normally in the tool holder).

The performance test will be executed in the main axes (x, y, z) and optionally also in spatial diagonals [6]. Up to 4 different lengths (500 mm, 1000 mm, 1500 mm and 2000 mm) in different axial or spatial positions will be measured. The deviations will be calculated as measured values (measured by the machine tool) minus calibrated distances between ball centres.

3.1. Dimensional properties

The standard is designed as a modular ball-bar artefact that can materialise 4 lengths:

- 500 mm,
- 1000 mm,
- 1500 mm,
- 2000 mm.

Materialised measure is the distance between two ball centres. The concept is shown in Fig. 1.

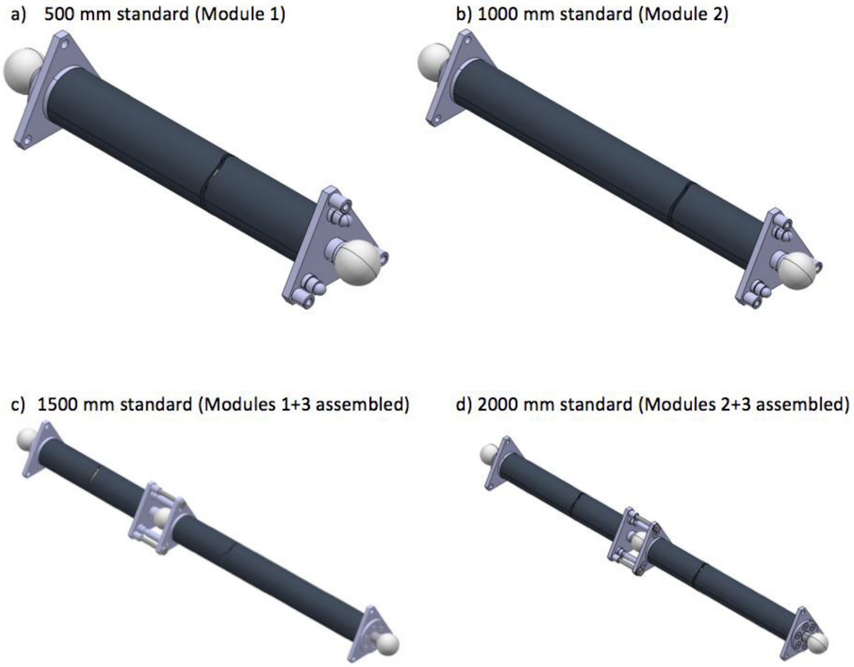

Fig. 1. Conceptual design of the standard.

3.2. Materials

Different materials are used for different constructional parts of the standard. The materials of the main constructional parts are listed below:

- Main body (tube) – composite material (carbon fibres in epoxy matrix),
- Bases (joints) – steel,
- Ball holders – steel,
- Compensator for thermal expansion – aluminium,
- Probing balls – ceramics.

Materials were chosen on the bases of experiences with similar standards. Temperature expansions, resistance against liquids (water, oils, …), bending and surface properties (probing elements) were considered while choosing materials. Composite material was chosen for the main body of the standard because of its rigidity, low temperature expansion and low weight (the standard should be easily transportable). Alternative material for the main body of the standard would be e.g. invar, which has similar properties as regards metrology (expansion, bending), but would be heavier and much more expensive. The ceramic material for probing balls has almost no equivalent alternative as regards surface properties (sphericity, hardness, resistance against liquids) and is therefore used worldwide in similar cases. Stainless still was chosen for all coupling elements due to its resistant to corrosion and machining properties. Economic aspects were considered as well. Aluminium is used for the "temperature compensator" due to appropriate and temperature expansion coefficient, which can be precise determined.

3.3. Design

The standard consists of three modules. Two modules (1 and 2) are ball standards of different lengths (Module 1 – 500 mm, Module 2 – 1000 mm) that can be used separately or in combination with Module 3 (which is only an extension and can't be used separately). Each module contains a "temperature compensator", which compensates thermal expansion of the composite tube (main body of the standard). Detailed design of modules 1 and 2 is shown in Fig. 2.

Fig. 2. Design of modules 1 and 2.

3.4. Compensator of thermal expansion

In order to achieve length stability in harsh environmental conditions, the standard is equipped with an active thermal expansion compensator (Fig. 3).

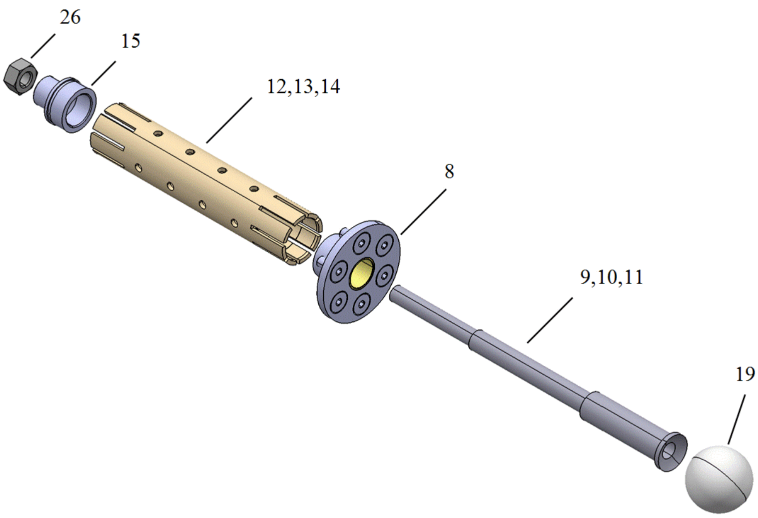

Fig. 3. Thermal expansion compensator.

The compensator is made of two different materials with significantly different thermal expansion coefficients. The tube (Pos. 12, 13, 14 in Fig. 3) is made of aluminium, while the flange (Pos. 8), the ball holder (Pos. 9, 10, 11), the tube cover (Pos. 15), and the nut (Pos. 26) are made of steel. The flange (Pos. 8) is attached to the composite tube – main body of the standard. If the ambient temperature is increased, the composite tube is expanding in "positive" direction, while the aluminium tube is expanding in the opposite direction and pulls the ceramic ball (Pos. 19) inside the main body of the artefact. The principle is shown in Fig. 4.

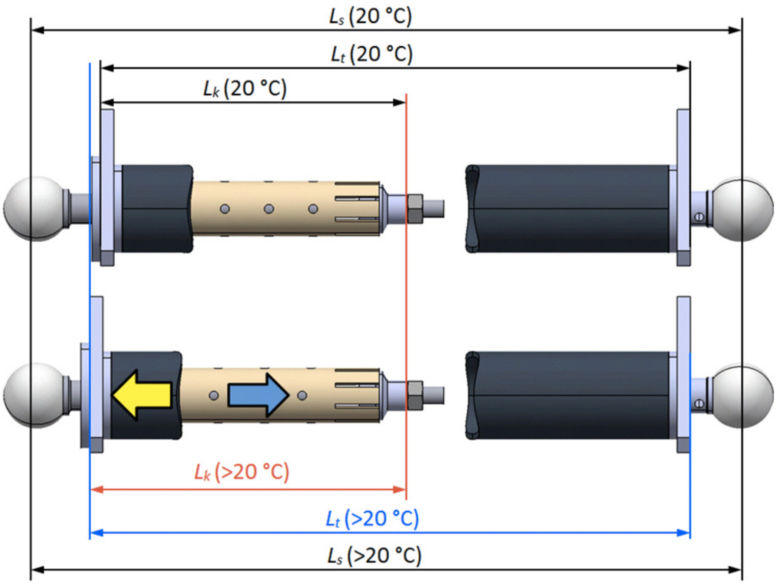

Fig. 4. Thermal expansion compensator – principle of operation.

3.5. Stability

Metrological stability of the standard in terms of ball distance changes is expected to be less than 1 µm/year. More critical feature could be length change due to bending and compression under different conditions of use (single module, combined modules, position in space – horizontal, vertical, spatial angle). Preliminary research was performed by using finite element method. The results have shown that the maximum expected error in terms of ball distance change was within 1 µm.

4. Traceability of the material standard

4.1. Metrological characterization

Metrological characteristics of the standard will be available in the form of a calibration certificate, stating 4 distances between ball centers (at nominal values 500 mm, 1000 mm, 1500 mm, and 2000 mm). The data will be available in paper as well as in electronic (txt file) form.

4.2. Calibration process

The standard will be calibrated by using tactile three coordinate measuring machine ZEISS UMC 850. Tree modules will be calibrated separately by applying normal measurement procedure (probing balls in at least 20 points each, repeating measurements 5 times for each distance, calculating average distances and standard deviations). The ball distances on combined modules (see Fig. 1 c and d) will be calculated by considering geometrical properties of joints between the modules.

4.3. Uncertainty of measurement

The standard will be calibrated with expected expanded uncertainty U = 2,1 µm + 3,3·10^{-6}·L (k = 2, level of confidence 95 %). The uncertainty [8] is defined by the verification test of the coordinate measuring machine used for calibration. The main following contributions to the uncertainty of measurement were considered:

- Geometrical properties of the coordinate measuring machine (CMM),
- Biases of the CMM measurement systems,
- Repeatability,
- Ambient temperature,
- Rigidity of the probing system,
- Geometrical properties of the standard to be calibrated.

Evaluated uncertainty of measurement will be confirmed by interlaboratoy comparison between the national metrology institutes involved in the project. Advanced statistical consistency tests [9] will be applied in order to check correctness of the calculated measurement uncertainty.

5. Application of the material standard

As indicated in chapter 3, the standard is aimed for checking geometrical properties of machining centers with various production volumes. Auxiliary equipment such as supports and holders shall assure simple and reliable positioning of the standard in different directions within the machine tool volume. The standard should be fixed only at one end, while the other end shall be free for expanding in the axial direction [10]. The most critical issue is bending of the standard. Fixing system was designed in a modular way in order to avoid too many different parts with same functions. The elements of the fixing system are shown in Fig. 5.

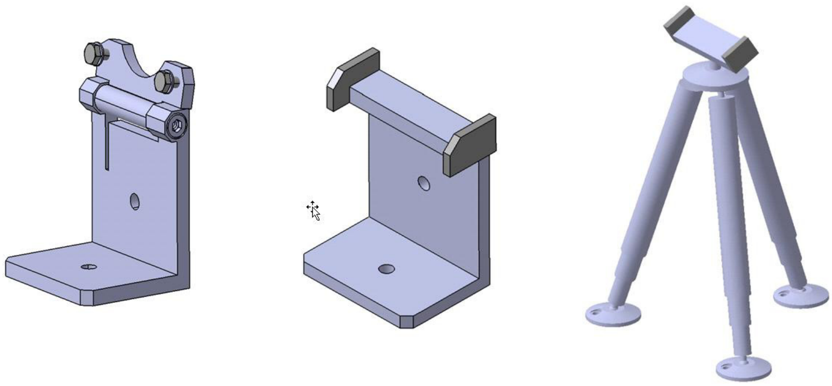

Fig. 5. Supporting and fixing elements for positioning the standard within machine-tool volume.

The standard is normally positioned along the machine-tool axes and main spatial diagonals. However, if the metrological characteristics of the machine tool to be inspected require measurements in special positions, the procedure can easily be adapted. Some examples of fixing the standard are shown in Fig. 6.

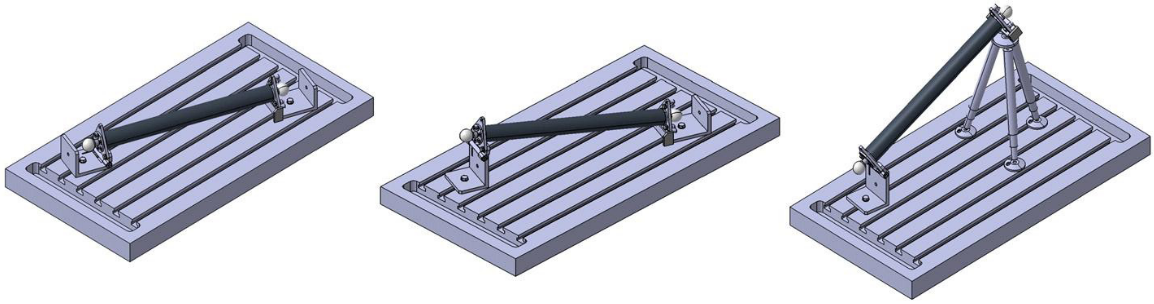

Fig. 6. Examples of positioning the standard within machine-tool volume.

Conclusion

Traceability of in-process 3D measurements is still not assured in proper metrological way on national, as well as on international level. However, quality system standards in advanced industries like automotive industry [11] set explicit rules on assuring traceability of all measurements in the production process. The project EMRP TIM [4] is aimed to solve this problem. It is currently in the design phase. The goal of this project phase was to design novel standards for assuring traceability of 3D measurements on machine tools in harsh environmental conditions. These standards should enable fast and reliable verification tests, as well as parametric error determinations on machine tools. The goal was reached by designing six 2D and 3D standards in accordance with examined measurement problems in in-process product inspection. Manufacturing techniques were defined as well. In the following project phases, the standards will be produced and calibrated. Purpose of the presented standard is to verify one-dimensional measurement capabilities of machine tools in harsh environmental conditions with temperature deviations extending ±10 °C. Theoretical analysis confirms measurement capabilities of the standard within an uncertainty range of 5 µm. The standard will be produced by three Slovenian unfunded industrial partners in the project: Gorenje Orodjarna, EMO Orodjarna and Veplas. It will be calibrated in the Laboratory for Production Measurement at the University of Maribor.

Very important part of the project is also development and validation of procedures for calibrating and verifying machine tools under harsh environmental conditions. The procedures will be validated by test measurements in real shop 23000, floor conditions. Unfunded industrial partners from different countries will be involved in this validation phase. One of the final goals of this validation phase is to determine uncertainty of measurement in calibration and verification [7]. It is expected that the contribution of short term and long term geometrical stability of the standards will have no significant influence on the total measurement uncertainty.

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