

Interaction between workpiece and CMM during geometrical quality control in non-standard thermal conditions

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Abstract

Industrial quality demands have resulted in increasing attention towards the thermal behavior of coordinate measuring machines. The influence of the workpiece on the measurement accuracy is hereby often disregarded. This can lead to significant measurement errors. The described research examines the interaction between the measurement device and the measured object. Four distinct measurement error types that result from non-standard temperatures are listed. Temperature variations during the measurement lead to the most challenging situation. The key to measurement accuracy lies in linking the measurement time to the accompanying temperature variation. The possibilities of this methodology are indicated by an experiment on a reference object. © 2001 Elsevier Science Inc. All rights reserved.

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1. Introduction

In today's industry, there is a growing need for flexible production systems. The increasing quality requirements imposed by the customer give rise to the integration of quality control on the shop floor. As a result, coordinate measuring machines (CMM) are more and more placed outside the protective environment of a metrology room, close to the production process. However, there the reigning ambient conditions are usually not within the boundaries set by international standardization. All dimensional measurements are theoretically considered at 20°C, thus shop floor conditions require managing the influence of deviating temperature on the measurement process [4].

The thermal behavior of a CMM can be dealt with by a software compensation of the thermal deformation of the machine, to complete the geometrical error compensation. Good results were achieved using this method [1,5,6,8,9]. The influence of the workpiece however is rarely dealt with, though it can cause huge errors in the resulting measurement even when—or sometimes because—thermal compensation for the machine is used.

This paper focuses on the interaction between the work-

piece and the CMM during quality control in a non-standardized environment. It first describes the types of errors that can occur and then proceeds to an appropriate measurement strategy for dealing with these errors. Finally the presented ideas are illustrated by an example.

2. The experimental set-up

The experiments are done on a bridge-type CMM with a work volume of $1.6 \times 1 \times 0.8 \text{ m}^3$. The manufacturer lists a volumetric accuracy (VDI) $u_3 = 5 + 5 * L * 10^{-3} \mu\text{m}$ (L in [mm]) within the temperature interval $(20 \pm 1)^\circ\text{C}$. In addition these accuracy specifications demand a maximum allowable temperature variation of $0.5^\circ\text{C}/\text{hour}$ and a maximum gradient of $0.5^\circ\text{C}/\text{m}$ over the machine. The CMM is equipped with self-adhesive scales that are anchored at the endpoints to the substrate material. Consequently the scales shrink and expand together with the machine guides. For this CMM the used materials for the X, Y and Z-guides are respectively granite, steel and aluminum.

Earlier work at PMA focused on the thermal deformation of the machine under consideration [5]. The effect of temperature based distortions of the machine geometry was studied and modeled. Subsequent compensation of the thermal errors of the machine makes it possible to isolate the

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effect of the workpiece's temperature variation on the measurement accuracy.

A stepped ball bar is used as a test piece (see Fig. 5). It consists of a steel basis on which six spheres are mounted. The nominal distance between two sphere centers is 300 mm.

The artifact is not calibrated, nor should it be for the conducted investigation. To get a reference value it is measured repeatedly at 20°C with the CMM under investigation. Together with the knowledge of the thermally induced deformations of the machine [5], these experiments give an insight to the influence of the workpiece on the CMM's repeatability in an extended temperature range (beyond the machine's specifications).

3. Measuring under non-standard temperature conditions

This section describes different thermal error types that occur during measurements. The distinction between them is made based on two criteria. The first criterion regards the variation of the temperature distribution in the machine structure. The temperature distribution can be stable (like in §3.1 and §3.2), or varying (like in §3.3 and §3.4), i.e., steady state or time dependent. The second criterion selects on the machine element involved. One can look at the relative position of the measurement probe (like in §3.1 and §3.3) or at the differential expansion of the linear scales and part (like in §3.2 and §3.4). Referring to the three-element system in Bryan's thermal influence diagram [3] the relative position of the measurement probe should be considered as the machine frame and the linear scales as the master element. The third element is the part that is to be measured.

3.1. Steady state effect of the relative probe position

The relative probe position (RPP) is defined as *the position of the probe-tip relative to the devices that read-out the scales, projected on the axis of the read-out unit under consideration*. The RPP, at a point in the measurement volume, depends on the temperature distribution and variation in the CMM. In Fig. 1 the definition of the RPP is illustrated. It varies along the machine coordinate system's (MCS) axis (axes) as indicated on the chart.

Measurements of a workpiece are normally performed in a local coordinate system (LCS) that is defined by the operator. Hence the measurement is done relative to the origin of the LCS. Thermal deformations of the machine shift the relative probe-position. If the RPP is constant throughout the measurement volume, it does not introduce an error in a relative measurement, because the error (RPP) in the measurement of the origin is exactly the same as the error made in the measurement of the point on the artifact.

If the RPP is not constant over the measurement volume, extra errors are introduced. For example, this can be caused

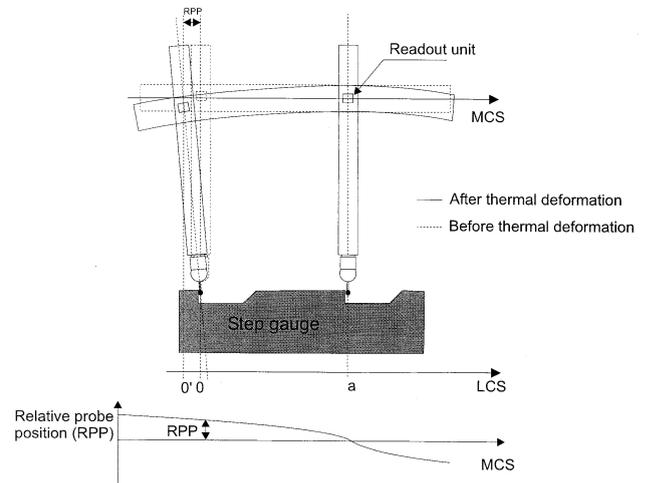


Fig. 1. Steady state error due to the thermal deformation of the machine.

by a vertical temperature gradient in the room. In this case the thermal error (RPP) at the origin of the LCS is no longer the same as the error at the point on the artifact. On the left-hand side of Fig. 1 for example the Z-axis is no longer perpendicular with the worktable of the machine. This deformation is the origin of a non-uniform RPP over the length of the measurement volume. The measurement of the left point, the origin, yields a bigger thermal error than the measurement of the right point, point a.

If the machine is equipped with a sufficient thermal compensation, this type of thermal error will be corrected for [1,6,9]. Some manufacturers rely on the machine design to reduce thermal distortions. The trend is to use lightweight materials with a high thermal conductivity to reduce thermal gradients over the elements, e.g., aluminum within the CARAT technology [1]. In that way the occurrence of non-constant RPP due to bending of machine elements is avoided.

3.2. Steady state differential expansion of workpiece and scale

Due to changes in ambient temperature both the CMM scales and the workpiece expand. In steady state the resulting error is caused by the nominal differential expansion (NDE) between the workpiece and the scale. As an example one can look at the measurement of a steel bar with length $L = 1$ m with an aluminum scale at temperature $T = 23^\circ\text{C}$. The coefficient of thermal expansion (CTE), α , of steel typically equals $12 \mu\text{m}/\text{m}\cdot^\circ\text{C}$. For the aluminum scale the CTE is $23 \mu\text{m}/\text{m}\cdot^\circ\text{C}$. The thermal error ϵ , relative to standard conditions ($T = 20^\circ\text{C}$) can be determined with formula 1.

$$\begin{aligned} \epsilon &= \Delta L_{\text{object}} - \Delta L_{\text{scale}} \\ &= \alpha_{\text{object}} \cdot L \cdot \Delta T_{\text{object}} - \alpha_{\text{scale}} \cdot L \cdot \Delta T_{\text{scale}} \end{aligned} \quad (1)$$

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