

Achieving precision measurements under non-standard environmental conditions

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Abstract. Geometric measurements should be made at standard temperature 20°C, otherwise errors due to thermal expansion of workpieces and scales will occur. If measurements in serial production have to be made at different temperatures, DIN EN ISO 15530-3 describes a technique to correct the measurement error by referring to a calibrated reference workpiece. We have investigated this approach theoretically and experimentally and present some results.

1 Introduction

Geometric measurements are affected by temperature changes because of the material-specific temperature expansion of workpiece and instrument. For that reason the environmental conditions have to be tightly controlled for precision measurements. In real-world applications, especially in production environments, it is often not possible or economically not affordable to control the environment to the standard temperature of 20°C that is required by the relevant national and international standards. This problem is even more demanding for many developing countries situated in areas with hot climate.

If the ambient temperature is measured and known, a numerical correction of the measurement values is in principle possible. However, it requires detailed knowledge about the internal structure of the coordinate measuring machine (cmm). Due to the at least 21 degrees of freedom of a 3-axes cmm the mathematical modelling is of prohibitive complexity for most users. Some manufacturers of cmm's integrate correction algorithms in their evaluation software, but typically only for expensive high-end instruments.

For the quality assessment in serial production we suggest the measurement strategy described in DIN EN ISO 15530-3 [1], that allows performing precision measurements under different environmental conditions and can be applied without special mathematical or engineering skills. The key idea is to calibrate a selected serial part and apply it as a reference for checking the conformity of all other produced parts of that type. Because the geometry and the material of the reference part are nominally equal to those of the serial parts, temperature changes will have more or less identical effects on both of them.

The measurement instrument, e.g. a coordinate measuring machine (cmm) is only needed to determine the geometrical difference between a workpiece under test and the calibrated workpiece. These differences will typically be of the order of a fraction of a mm and only these values will be affected by temperature changes due to deformations of the instrument

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and the workpieces. These errors caused by thermal expansion are typically of the order of 10^{-5} (relative) and acting on values smaller than 1mm can be neglected.

2 Theory

Let l_{20} be the length of a workpiece measured at standard temperature and l the length of that same workpiece measured at some temperature $T = 20^{\circ}\text{C} + \Delta T$. With the coefficient of thermal expansion α we get equation 1:

$$l = l_{20}(1 + \alpha \cdot \Delta T) \quad (1)$$

In general the workpiece and the scale will have different temperatures so that we can write equation 1 for both of them, identifying them with the index “wp” or “sc”, respectively:

$$\begin{aligned} l_{sc} &= l_{20sc}(1 + \alpha_{sc} \cdot \Delta T_{sc}) \\ l_{wp} &= l_{20wp}(1 + \alpha_{wp} \cdot \Delta T_{wp}) \end{aligned}$$

This leads to the correction formula:

$$l_{20wp} = l_{wp} \frac{1 + \alpha_{sc} \cdot \Delta T_{sc}}{1 + \alpha_{wp} \cdot \Delta T_{wp}} \quad (2)$$

In practical applications in production however, the continuous measurement of temperatures might be tedious and the coefficients of thermal expansion of workpiece and especially of scales might not be known with the required precision. In this case a reference workpiece of the same kind as the regular ones might be calibrated under standard conditions. If both the regular workpieces and the calibrated workpiece are then measured under similar non-standard conditions (Fig. 1), the measurements can be corrected by referring to the known calibration value l_{20rwp} (equation 3).

$$l_{20wp} = \frac{l_{20rwp} \times l_{wp}}{l_{rwp}}$$

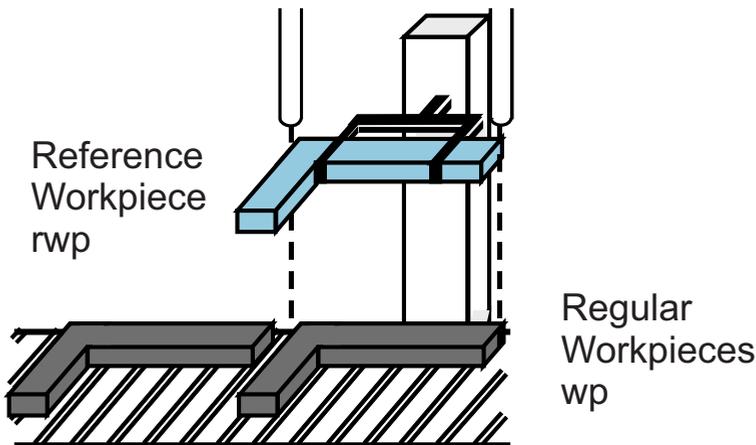


Fig. 1. Serial test in production referring to a calibrated reference workpiece rwp

3 Experiments and Simulation Calculations

We tested this approach experimentally with a number of workpieces, ranging from simple end gauges to complex shaped test workpieces (Fig. 2). Using a cmm Werth VideoCheck HR without internal temperature compensation for the measurements we varied the room temperature between 16°C and 24°C. In all cases the resulting errors were in the order of only a few μm . As an extreme case we did one measurement run at 40°C, using a precision optoelectronic probe (Heidenhain SP25, Fig. 3). Though the error due to thermal expansion in this case was more than 80 μm , we could correct it to less than 2 μm .

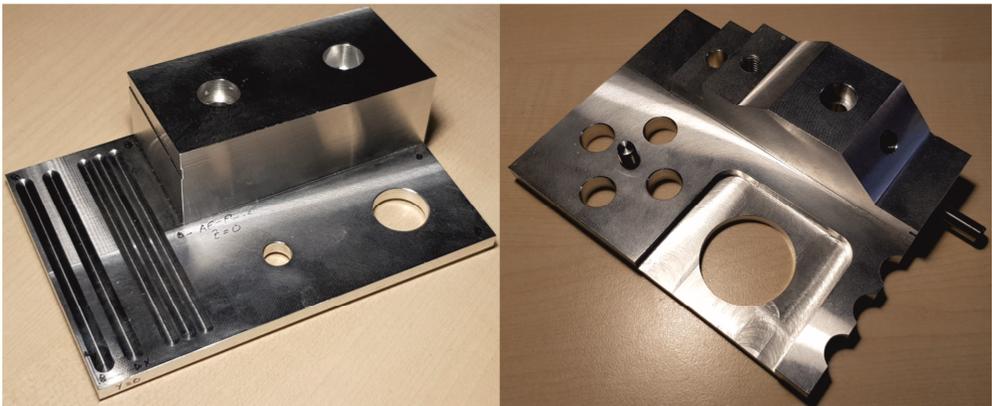


Fig. 2. Complex shaped test workpieces used for our experiments

Using the simulation software ANSYS we checked the effect of heat exchange between workpiece and environmental air. The temperature distribution in the workpiece is then inhomogeneous (Fig. 4), but this effect will also occur in the reference workpiece and in our case studies was to a good approximation cancelled by the correction strategy.

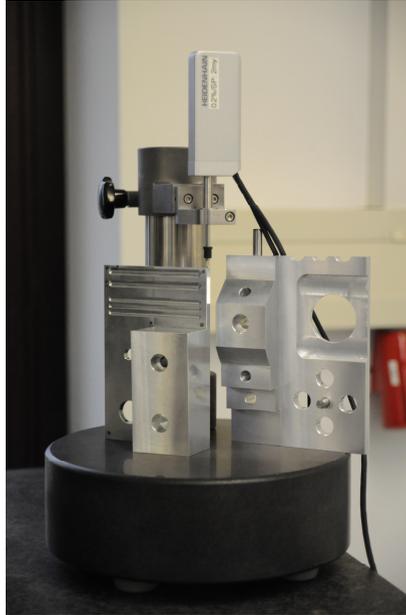


Fig. 3. SP25 probe with different workpieces

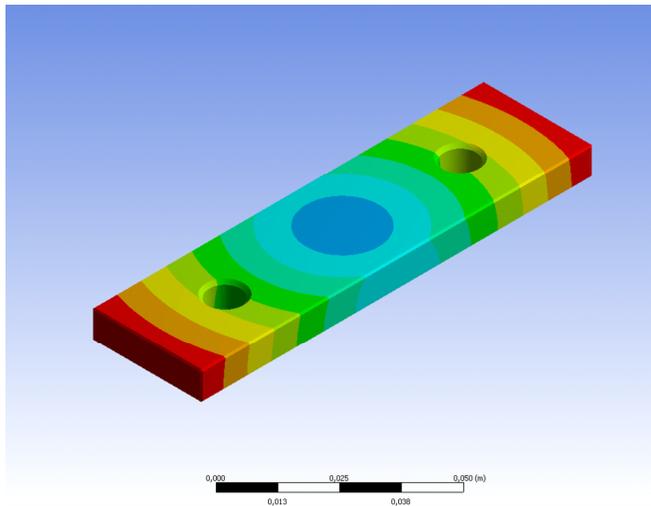


Fig. 4. Colour-coded display of the temperature distribution of a workpiece caused by heat exchange with the ambient air

An in-depth error analysis according to GUM can be found in [2]. Considering realistic assumptions we estimate the expanded uncertainty of a length measurement of a workpiece with about 100 mm length to $5\mu\text{m}$. The analysis of the error budget shows that the main error contributions are the measurements of the actual lengths of workpiece and reference workpiece and variations in material properties in serial production.

All these measurements, simulations and estimations were applied to homogeneous workpieces. Our investigations on inhomogeneous workpieces built from aluminium and steel parts showed a limitation of our method due to warpage of the workpieces.

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