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# Dynamic Length Metrology (DLM) for measurements with sub-micrometre uncertainty in a production environment

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**Abstract**

Conventional length metrology for traceable accurate measurements requires costly temperature controlled facilities, long waiting time for part acclimatisation, and separate part material characterisation. This work describes a method called Dynamic Length Metrology (DLM) developed to achieve sub-micrometre accuracy on metal parts, or micrometre accuracy on polymer parts, directly in a production environment. The method consists in the simultaneous measurement of all quantities affecting dimensions of a part over time (dynamically), involving a number of sensors and reference artefacts, followed by mathematical or numerical modelling of the thermo-mechanical effects. It is hereby possible concurrently to predict condition-specific material properties as well as part dimensions at any point, time, temperature, humidity, etc. Knowing all systematic errors and influencing factors, and their combined effect, on a given length, it is possible to calculate the corrected length at 20°C, zero measuring force, etc. An estimation of the measurement uncertainty U can be obtained following the guidelines of the GUM, dimensional values and their uncertainties being the final result of the analysis. Preliminary investigations have indicated that the approach is viable, either using analytical modelling or FEM. An expanded uncertainty (k=2) lower than 0.4 µm was achieved using a steel gauge block as workpiece.

Keywords: Metrology, low uncertainty, production environment

## 1. Introduction

The work introduces the method called Dynamic Length Metrology (DLM) to achieve sub-micrometre accuracy in a production environment, and accurate measurements, at micrometre level, on parts made from dimensionally relatively less stable materials such as, e.g., polymers. The new method consists in simultaneously to measure all quantities affecting dimensions of a part over time (dynamically), using a series of sensors and references, and apply mathematical or numerical modelling of the thermo-mechanical effects to concurrently predict task-specific material properties and part dimensions at any point, time, temperature, humidity, etc. In principle, if all systematic errors and all influencing factors and their effect on the measurands are known, it is possible to develop a metrological model calculating the corrected length at 20°C, zero measuring force, etc. An estimation of the uncertainty of the measurement *U* can be obtained following the guidelines of the GUM [1]: Dimensional values and their uncertainties are the final result of the analyses. Table 1 illustrates the impact of the new method in terms of requirements. DLM can be implemented at several levels:

- Stand-alone unit complete of sensors and software
- Solution complete of sensors and software for use together with a measuring fixture in the production
- Solution complete of sensors and software for use on a Coordinate Measuring Machine (CMM).

Preliminary investigations have indicated that the approach is viable [2], [3].

**Table 1.** Main requirements in conventional vs. Dynamic Length Metrology (DLM).

| Requirements for accurate measurements using conventional length metrology | Requirements for accurate measurements using Dynamic Length Metrology (DLM) |
|---|---|
| • Costly temperature controlled facilities<br>• Long waiting time for part acclimatization<br>• Separate part material characterization | • Directly in production environment<br>• Dynamic multi-sensoring system<br>• Mathematical and numerical modeling |

## 2. Experimental investigation using gauge blocks

Two gauge blocks made of steel, and tungsten carbide, respectively, have been used in an investigation using one gauge block as workpiece and the other one as reference [2].

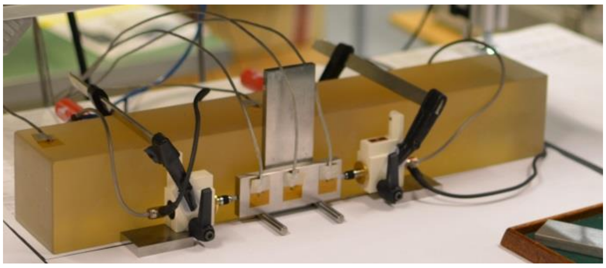

**Figure 1.** Set-up for DLM on gauge blocks [2].

By heating the test gauge block to approx. 25˚C and zeroing the equipment using the second gauge block, concurrent measurements of two lengths and four temperatures over time were performed. From the data, both an analytical approach and one using Finite Element Modelling (FEM) can be applied, as described in the following.

## 3. Analytical solution

The analytical solution uses the length and temperature measurements to calculate the corrected length at 20°C by concurrently characterizing the material coefficient of thermal expansion (CTE) of the part during measurement. It should be noted that the value determined in this way is an apparent (task specific) CTE. The analytical solution is based on minimising the error in length measurement by finding the optimum values of the model parameters in accordance with the actual measurements. The model is described by a linear expression containing the parameters CTE, length and temperature:

$$L\,(t) = L_{ref} + \Delta L(t) - f(T,t)$$

Figure 2 shows the calculated length as a function of the measuring time for a set of 9 repeated runs on the steel gauge block. It can be seen that the result converge to a stable calculated length. Over time more input is processed by the analytical solution and a more stable solution is obtained. Uncertainties are calculated taking into account the uncertainty of repeatability, inductive probes, reference gauge block and of the temperature sensors. Results from a single cooling curve and considering a measuring time of 600 s are already satisfactory, as shown in table 1.

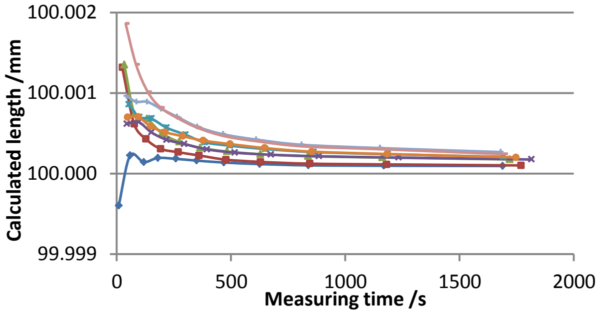

**Figure 2.** Calculated length at 20°C vs. measuring time.

## 4. Numerical solution

The numerical model has to solve for two different field quantities: the transient temperature field and the transient displacement field. The basic field equation that has to be solved in the thermal model is the standard heat conduction equation by Fourier while the influence from the surroundings is in this case modelled via Newton's law of cooling, which is applied as boundary conditions on the surface. Temperature was measured at three different points on the gauge block (see Fig. 1).

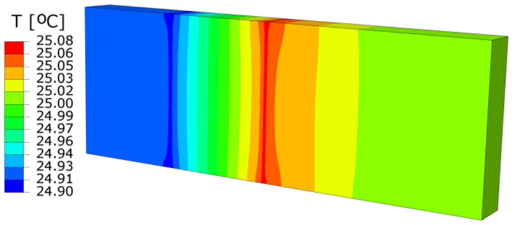

**Figure 3.** Contour plot of the reconstructed initial non-uniform temperature distribution within the steel gauge block.

Based on these temperatures, the thermal model is used to reconstruct the overall transient temperature field, see Fig. 3. One temperature only was considered for calculations during cooling down.

The basic field equations that have to be solved in the mechanical model are the three static equilibrium equations. Hooke's law and linear decomposition of the strain tensor as well as small strain theory are applied together with the expression for the thermal strain.

An inverse modelling procedure is necessary, where the model through an optimization algorithm is able to adjust the local CTE value, being the dominating parameter, such that the overall value from the simulation fits what has been measured during the dynamic length measurements.

The result from the mechanical model is the displacement field at the reference condition from which the length variation between the two centre points on the steel gauge block can be extracted. On this basis the length of the steel gauge block is calculated similarly to the analytical solution, considering data over a measuring time of 600 s.

The expanded uncertainty of the mechanical model is calculated as twice the standard deviation of the simulated lengths at the reference conditions.

## 5. Results

Calculated length and uncertainty values obtained using the analytical approach and those using FEM, considering measurements over 10 min, are compared in Table 1 with values from interferometric calibration. The comparison indicates that the DLM approach allows achieving sub-micrometre accuracy on metal parts after 10 min of measurements directly in a production environment.

**Table 1** Comparison of calculated and calibrated values for a steel gauge block length. Uncertainties are expanded (k=2).

| | |
|---:|---|
| **Length from calibration certificate $L_{ref}$ /mm** | 100.000138 |
| **Calibration uncertainty $U_{ref}$ /µm** | 0.052 |
| **Analytically calculated length $L_{ana}$ /mm** | 100.000277 |
| **Uncertainty of analytical length $U_w$ /µm** | 0.31 |
| **$E_n$** | 0.44 |
| **Numerically calculated length $L_{num}$ /mm** | 100.000239 |
| **Uncertainty of numerical length $U_w$ /µm** | 0.2 |
| **$E_n$** | 0.49 |

## 6. Conclusions

Dynamic Length Metrology (DLM) allows achieving sub-micrometre accuracy on metal parts after 10 min of measurements directly in a production environment.

## Acknowledgments

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### References

[1] BIPM, Evaluation of measurement data — Guide to the expression of uncertainty in measurement, JCGM 100:2008, GUM 1995 with minor corrections.

[2] L. De Chiffre, M.M. Gudnason, D. Gonzalez-Madruga, Dimensional measurements with submicrometer uncertainty in production environment, Proceedings of the 15th Int. Conf. Exhib. – Leuven (2015).

[3] L. De Chiffre, D. Gonzalez-Madruga, G. Dalla Costa, L.C. Neves, I. Jespersen, Accurate characterisation of post moulding shrinkage of polymer parts, Proceedings of the 15th euspen International Conference – Leuven (2015).

[4] A. Mohammadi, M.R. Sonne, D.G. Madruga, L. De Chiffre, J.H. Hattel, Defining Allowable Physical Property Variations for High Accurate Measurements on Polymer Parts, 14th Int. Conf. of Numerical Analysis and Applied Mathematics - ICNAAM 2015 Conference, Rhodos.