

A NEW HIGH PRECISION LENGTH MEASURING MACHINE

R. Thalmann

Swiss Federal Office of Metrology (OFMET)
Lindenweg 50, CH-3084 Wabern

Abstract

In a joint project of OFMET and a Swiss manufacturer (SIP), a new measuring machine for the calibration of length standards has been built. The basic features are: mechanical structure with optimum stability and small errors of motion, low Abbe offsets, high resolution probing head, and the use of a laser interferometer. This allows to achieve a measurement accuracy in the order of $0.05 \mu\text{m}$ for standards of good quality. All operations can be numerically controlled. Using different options for the probing head, the measuring machine can be applied for the calibration of ring and plug gauges, spherical standards, screw gauges, step gauges and line scales. Besides a description of the machine and its key elements, a detailed estimation of the measurement uncertainty will be presented.

Résumé

Dans un projet commun de l'OFMET et une entreprise Suisse (SIP), une nouvelle machine à mesurer pour des étalonnages de longueurs a été développée. Les propriétés principales sont: structure mécanique avec stabilité optimale et petites erreurs de guidage, faible offset d'Abbe, palpeur à haute résolution, et l'emploi d'un interféromètre à laser. Ceci permet d'obtenir une incertitude de

qualité. Toutes les opérations peuvent être contrôlées numériquement. En utilisant différentes options pour la tête de mesure, la machine peut être appliquée pour l'étalonnage de jauges bagues, tampons et sphériques, de jauges de filetage, de cales étagées et d'étalons à traits. A part d'une description de la machine et de ses éléments clef, une estimation détaillée de l'incertitude de mesure sera présentée.

General description

To satisfy the ever increasing demand of industry for higher accuracy and more versatility for the calibration of length standards, a new length measuring machine has been built at the Swiss Federal Office of Metrology (OFMET). The principal requirements were to achieve a measurement uncertainty in the order of $0.05 \mu\text{m}$ to $0.1 \mu\text{m}$ for diameter standards, numerically controlled operation and the flexibility to calibrate a variety of different standards such as ring and plug gauges, spherical standards, step gauges, thread gauges and line scales. The machine should have two axes, a horizontal measuring axis and a vertical axis which allows to cross over the measured object and to measure on different heights.

The basic design requirements with respect to the geometry, the range and the guide errors were best fulfilled by the gantry of a commercial coordinate measuring machine (Société Genevoise d'Instruments de Physique SIP CMM5). The lower part, i.e. the base and the table, was constructed by SIP especially for this machine (Fig.1). The entire machine is made of cast iron and has a total weight of 3000 kg. The horizontal axis with the hydrostatic bearing has a traverse length of 700 mm. The vertical axis consists of a grinded cylinder and offers 350 mm range. The table is grinded flat with T-slots and small V-grooves. It is kinematically mounted on the base and sufficiently large to accommodate different accessories and a number of gauges to be temperature stabilized before measurement.

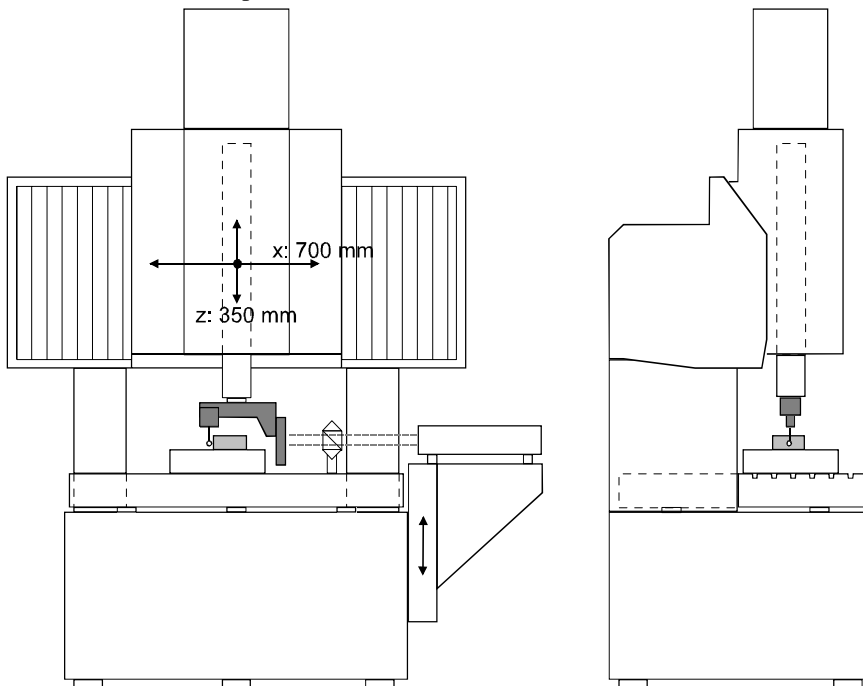


Fig.1 Length measuring machine SIP/EAM-LMM5.

mesure dans l'ordre de $0.05 \mu\text{m}$ pour des étalons de bonne

Motion accuracy of the linear guideways

Metrologically most important are the guide errors of the axes. In particular, a small pitch of the measurement axis will allow to minimize errors caused by an Abbe offset. For certain configurations, an Abbe offset between the measurement line and the scale given by the beam of the laser interferometer cannot be avoided. Figure 2 shows a measurement of the rotational error of the x-axis around the y-axis (R_{xy} , pitch) carried out with an angular interferometer. It amounts to $4.2 \mu\text{m/m}$ (smaller than $1''$) over the entire range and is smaller than $1.5 \mu\text{m/m}$ over any 100 mm range. The fact, that it is repeatable and stable in time allows for correction using error mapping. In table 1, the measured values of most of the guide errors of the two axes are summarised. The measurements were done with an angular interferometer, a straightness interferometer, electronic levels and a granite square. It has to be noted, that these values are all raw data, without any corrections.

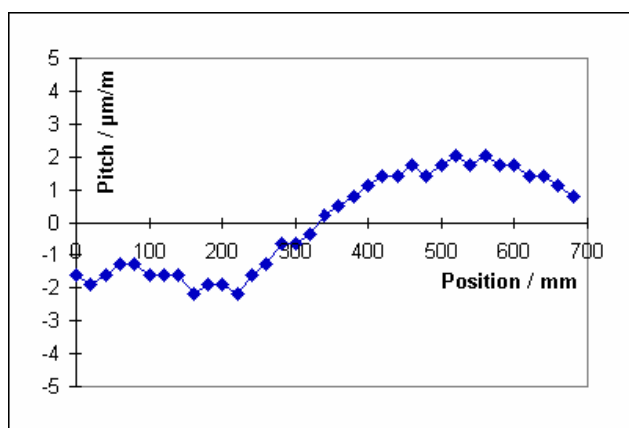


Fig.2 Pitch error of the horizontal guideway (x-axis).

	x-axis	z-axis
Translational errors		
straightness (μm)	T_{xy} 2.5	T_{zx} 1.0
straightness (μm)	T_{xz} 0.9	T_{zy}
Rotational errors		
pitch ($\mu\text{m/m}$)	R_{xy} 4.2	R_{zy} 0.6
yaw ($\mu\text{m/m}$)	R_{xz} 3.0	R_{zx}
roll ($\mu\text{m/m}$)	R_{xx}	R_{zz} 20
Angle ($\mu\text{m/m}$)		$z \perp x$ 1.5

Table 1. Guide errors of the two axes of the measurement machine.

The measurement system

The measurement system is sketched in Fig.3. The \cap -shaped cast iron body, which is fixed on the vertical axis column, has on its left the inductive probe and on the right side the reflector of the plane mirror interferometer. This arrangement with the object in a fixed position and a moving measurement head allows to fulfill strictly the Abbe principle for gauges smaller than $\varnothing 250 \text{ mm}$. For internal diameter measurements, the probe moves only in

the horizontal measurement direction, whereas for external diameter, the vertical axis is used to overcross the object. Thanks to the plane mirror reflector, the interferometer signal is not lost during this operation.

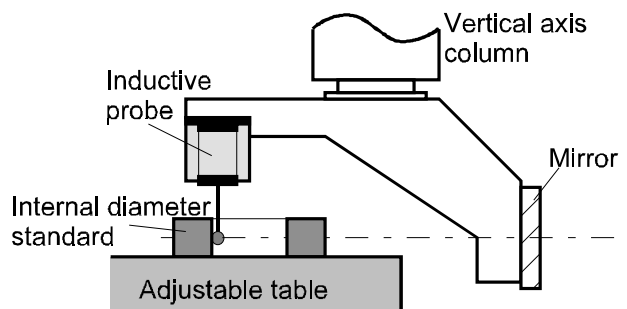


Fig.3 Measurement heads for internal and external diameter measurements respecting the Abbe principle.

The measurement scale is realised by a laser interferometer (laser HP 5518A, high stability plane mirror interferometer HP 10706B), which provides a resolution of 5 nm. The laser source can be adjusted in height to the level of the measurement object, the interferometer can be displaced to approach as much as possible the mirror in order to reduce dead path and turbulence effects.

For the probing system, an inductive parallelogram type system (Cary 1-Dim) with a spherical ruby stylus is used. Despite its excellent linearity and the small measurement forces it is in fact only used as a zero detector. For each measurement, several points at different deflections are recorded and finally extrapolated to zero (Fig.4), resulting in a theoretical probing point corresponding to zero measurement force. From repeatability measurements, a standard deviation of 4 nm has been determined for the zero point probing, which is close to the theoretical limit given by the digital resolution of the inductive probe (10nm) and of the laser interferometer (5nm).

The stylus constant, which is the difference between left and right contact probing, is essentially given by the diameter of the sphere of the stylus and any asymmetry of the bi-directional inductive probing system. This parameter is determined from measurements of a 5 mm gauge block. The length of the gauge block has been measured on a gauge block interferometer with an uncertainty of 15 nm. The gauge block has been suitably selected to have minimum flatness deviations, assuring the interferometric length to be as close as possible to the mechanical length between the centres of the measurement faces. The standard deviation of repeatedly determined stylus constants typically amounts to 5 nm. The stability of the stylus constant is usually observed to be within 10 nm over several days, however, sometimes unexplained changes in the order of 50 nm in one day were observed. It is therefore essential to monitor this constant regularly.

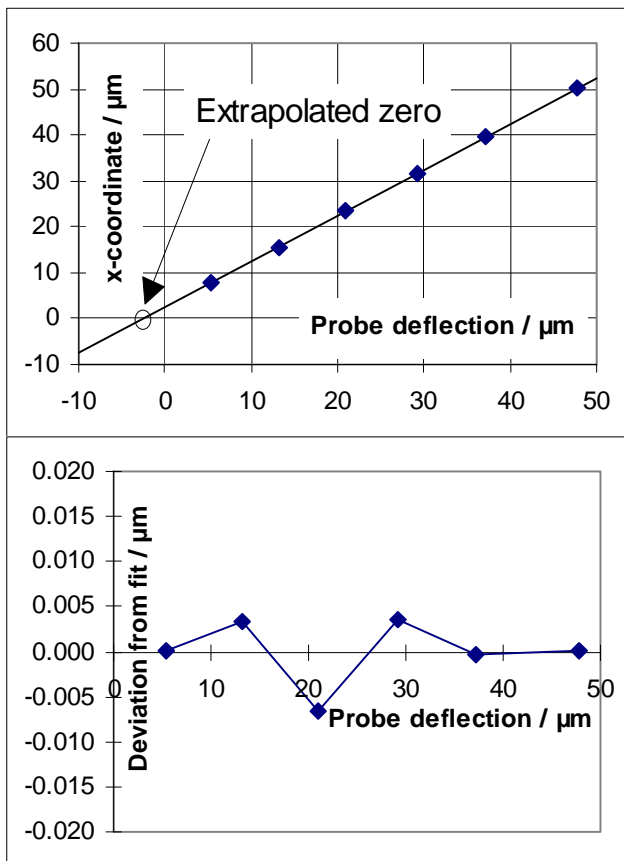


Fig.4 Extrapolation of the deflection of the inductive probe system to zero measurement force and deviation of linearity of the probe.

Alignment stage

To avoid cosine errors, the measurement object must be aligned in one or two rotational axes. In addition, for cylindrical or spherical standards, the location of maximum diameter must be found. To do this, a heavy alignment stage with x/y-tilt and y-translation has been built. A smooth translation is most important for a proper location of the maximum diameter point. The straightness has been measured by probing the measurement face of a gauge block which has been translated by the stage. The straightness deviations were found to be below 10 nm for 0.5 mm, 30 nm for 1 mm and 70 nm for 15 mm travel.

Step gauge measurement

For larger objects, in particular step gauges, an alternative measurement head has been built (Fig.5), where the interferometer reflector and the stylus probe are not on the same height. Thanks to the small pitch error of the horizontal axis, the Abbe error is usually smaller than 0.05 μm and can be - if adequate - compensated using error mapping.

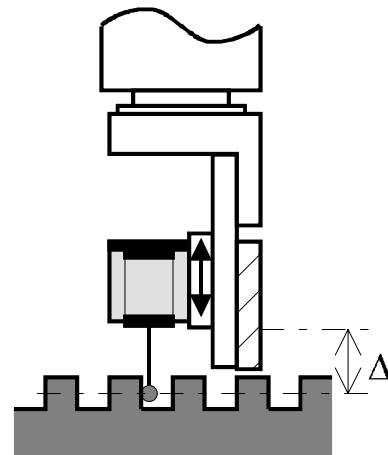


Fig.5 Measurement head for large objects, in particular for step gauges.

Measurement of screw threads

The calibration of the pitch diameter of both, internal and external screw threads is carried using double-ended styli with spherical probes, the diameter of which is chosen such as to probe the thread as close as possible at half height of the flank. The probing into a V-groove necessitates an additional degree of freedom. This is achieved by mounting the inductive probe on a flexure hinge which allows the probe to be free in the vertical direction (Fig. 6). Once the probe touches correctly the thread groove, the z-axis of the measurement machine is displaced until the flexure hinge reaches the position of zero deflection. This allows to avoid any residual cross-talk of the hinge-deflection in the measurement direction. The probe constant is calibrated using a gauge block, the diameter and roundness of each sphere is calibrated separately using other instruments.

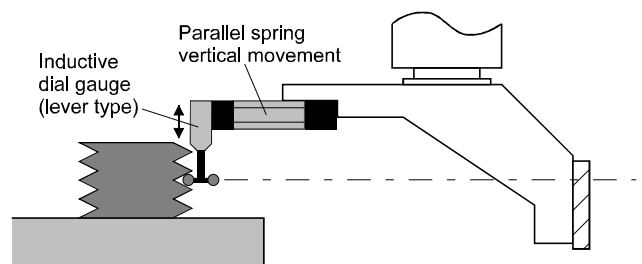


Fig.6 Measurement head for the calibration of the pitch diameter of internal and external screw gauges.

Line scale measurement

The calibration of line scales can be carried out using the optical measurement unit shown in Fig.7. It allows the Abbe offset to be kept below 2 cm. The head is equipped with a microscope, a CCD camera and a fibre optic illumination system. The observation and localisation of the scale marks is carried out visually with respect to reference lines projected onto the video monitor. The nominal position of the scale marks is located by the numeri-

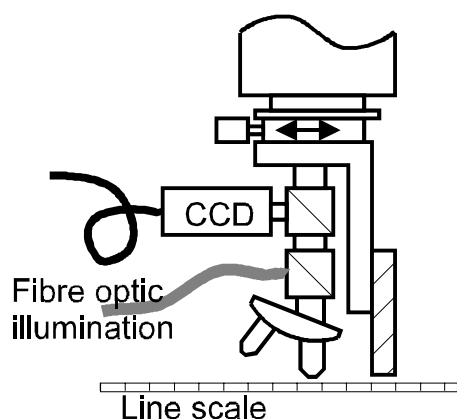


Fig.7 Measurement head with optical microscope for the calibration of line scales.

ally controlled positioning of the horizontal axis, the fine positioning is carried out manually with the help of a highly sensitive linear stage between the column and the measurement head.

Uncertainty of measurement

The performance of the measurement machine can best be illustrated with an example of the estimation of measurement uncertainty. According to the rules of the *ISO Guide to the Expression of Uncertainty in Measurement*, the uncertainty budget has been evaluated for the example of the calibration of a **ring gauge of 40 mm diameter** (Table 1). The example shows, that the measurement uncertainty is essentially limited by the probe (stability of the probe constant, digital resolution of the probe when searching the point of maximum diameter, and calibration of the spherical probe using a gauge block) and the quality of the calibrated standard (typical form deviations are assumed for roundness and straightness of the generatrix of a good quality ring gauge). The estimated uncertainty of measurement has been confirmed by the results of a recent (not yet published) comparison within EUROMET.

Quantity	Standard uncertainty	Sensitivity coefficient (L : length)	Uncertainty contribution
Laser frequency	10^9	L	0.04 nm
Index of refraction	$8 \cdot 10^{-8}$	L	3.2 nm
Material temperature measurement ($\alpha = 11.5 \cdot 10^{-6} \text{ K}^{-1}$)	0.003 K	$11.5 \cdot 10^{-6} \cdot L \text{ K}^{-1}$	1.4 nm
Uncertainty of expansion coefficient ($ T - T_{\text{ref}} < 0.05 \text{ K}$)	$0.6 \cdot 10^{-6} \cdot \text{K}^{-1}$	$0.05 \cdot L \text{ K}$	1.2 nm
Residual cosine error	0.06 mm/m	$3 \cdot 10^{-5} \cdot L$	0.07 nm
Residual pitch error (Abbe offset $< 3 \text{ mm}$)	$10 \mu\text{m}/\text{m} \cdot \text{m}^{-1}$	$0.003 \cdot L \text{ m}$	1.2 nm
Repeatability of diameter measurement	10 nm	1	10 nm
Searching the point of maximum diameter	12 nm	1	12 nm
Form deviations of calibrated specimen (ring gauge)	20 nm	1	20 nm
Stylus constant (repeatability, stability)	15 nm	1	15 nm
Uncertainty of gauge block used for stylus constant	8 nm	1	8 nm
Combined standard uncertainty			31 nm
Expanded uncertainty of measurement (coverage factor $k = 2$)			$U = 62 \text{ nm}$

Table 1 Example of a measurement uncertainty budget for the calibration of a ring gauge of 40 mm diameter.