The dimensional calibration of piston-cylinder units to be used for pressure metrology and the re-determination of the Boltzmann constant

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Abstract: Measurement procedures for the dimensional calibration of piston-cylinder type primary pressure standards which are intended to be used in a project for the re-determination of the Boltzmann constant are described. A numerical post-processing procedure is described to generate precise three-dimensional data sets from the 1D data sets. These data sets are required for the effective area determination of the pressure standards. Typical measurement results are discussed.

1. INTRODUCTION

Primary gas pressure standards up to 2 MPa are realized by pressure balances with piston-cylinder assemblies as major measuring components. The nominal effective area of such piston-cylinder units (PCU) varies typically between 5 cm^2 and 20 cm^2 corresponding with diameters ranging from 25 mm to 50 mm.

The effective area of pressure balances is usually calculated by using Dadson's theory [1]. The calculation is based upon dimensional input data.

2. RE- DETERMINATION OF THE BOLTZMANN CONSTANT

PTB and other NMIs run a project towards the re-determination of the Boltzmann constant k_B. As k_B is the proportional constant between thermal and mechanical energy, the project may lead to a new definition of the Kelvin [2]. The chosen realization is based on a Dielectric Constant Gas Thermometer (DCGT) and strongly depends on absolute pressure metrology in the range up to 7 MPa [3]. The required relative standard uncertainty should be as low as $1.0 \cdot 10^{-6}$ (1 ppm). For typical primary piston-cylinder assemblies with nominal effective areas of 5 cm^2 to 20 cm^2 the standard uncertainties of the three-dimensional coordinate data should lie, in dependence on the PCU size and uncertainty correlation model, in the range of 6 to 18 nm.

Six piston-cylinder assemblies made of tungsten-carbide, three with 20 cm^2 (Ø 50 mm) and three with 2 cm^2 (Ø 8 mm) nominal effective area, with the operation pressure ranges of 0.7 MPa and 7 MPa, respectively, were ordered by PTB to be used in the k_B experiments.

3. MEASUREMENT EQUIPMENT FOR HIGH PRECISION DIMENSIONAL CALIBRATION OF CYLINDERS

3.1. Coordinate measurement machines

In principle, the 3D calibration of piston-cylinder pressure standards may be a typical measurement task for 3D coordinate measuring machines (CMM). However, the measurement uncertainty of CMMs generally is larger than approx. 0.5 µm, in many cases larger than 1 µm. These values exceed the requested uncertainty target by more than one order of magnitude. New developments in the field of micro-CMMs already touch the interesting standard measurement uncertainty class of $u <$ 50 nm, but the probe shaft length often severely constrains the axially reachable surface to some few mm [5].

3.2. Form measurement instruments

For roundness measurements with the lowest achievable measurement uncertainty, a high precision roundness instrument (modified RTH Talyrond 73) in multi-step error separation mode is utilized. With that instrument, an uncertainty of u = 3 nm can be achieved [6].

For combined roundness, straightness and parallelism measurement a modified cylinder form instrument (MarForm MFU8PTB) is used [7].

3.3. Diameter measurement instruments

The MFU8 can also be used for two-point diameter measurements in the $u >$ 25 nm standard uncertainty range, because PTB's version was extended by a plane-mirror interferometer. Two-point tactile contacting length and diameter measurements with the lowest achievable uncertainty can be performed with PTB's reference length comparator KOMF [8]. That instrument is capable of achieving uncertainties of $u <$ 10 nm.

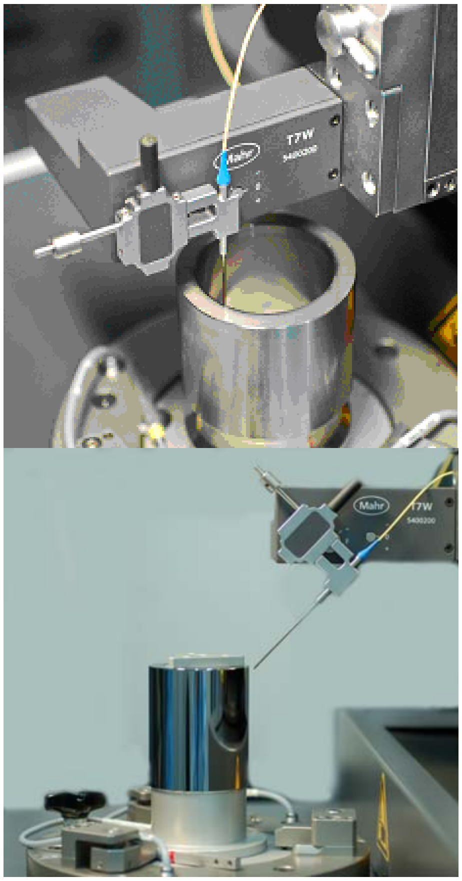

Fig. 1 *Optical probe "WhitePoint" while measuring an inner (upper) and an outer (lower) surface of a PCU. The swivel axis in the upper image is moved to the 0° position, such that the 90° beam of the probe is enabled. In the lower image the swivel axis is positioned to the 45° direction to enable the corresponding 45° beam of the probe system. This measurement geometry allows the scanning of the artifact with less geometrical constraints than at the 0° swivel axis position and is more stable than the 90° position.*

3.4. Multi-purpose cylinder measurement machine MFU110WP

The MFU110WP [9] is equipped with a high speed rotary table and interchangeable probe systems. Among these are systems for both size and form measurements, and in addition, special purpose probe systems, as, e.g., the probe system 1320D, which is optimized for diameter measurements. The machine control eliminates most guide error influences on measured profiles by internally subtracting reference data which are gained by capacitive scanning of an internal metrology frame during positioning.

Most cylinder form measurement machines can only measure planar, i.e. roundness or axial straightness profiles of the cylinders [10]. The MFU110WP additionally is able to scan the cylinder helically by moving its rotary table and Z-axis in parallel [11]. This measurement mode is advantageous for the numerical calculation of the effective area of the pressure balances, because it provides the most complete information on the piston and cylinder bore topography. However, the needed measurement time, drift effects, and wear of the contacting element limit the usefulness of such a scanning mode when operated by mechanical contacting.

To overcome this limit, the MFU110WP features an additional optical feeler system based on a heterodyne white light interferometer, which can acquire data with high speed. This system makes it possible to scan a full cylinder surface with high data density within less than a minute [11]. Of course, such high speeds should be avoided when the stability and noise level of the measurement signal shall be minimized as it is in the case of the application in the Boltzmann project.

The optical probes can be used with different light emission angles. This operation mode is supported by the swivel axis of the cylinder form instrument (Fig. 1).

3.5. Measurement set-up and artefact clamping

The precision of the dimensional calibration strongly depends on the reproducibility of the measurement positions. This is especially important when more than one measurement instrument is used for the full calibration procedure. Therefore, special artefact clamping tools based on kinematical mounts were manufactured. They enable an easy and reliable positioning of the artefact to be measured.

The system is based on clamping disks with kinematic mounts. These ensure a fast and reliable positioning. The kinematic mounts consist of precision rollers at 120° displaced positions of a circle which are glued to the clamping disks and their counterparts at the rotary tables of the MFU110WP and KOMF which are composed of a pair of balls. A notch-nose pair breaks the 120° symmetry and thus ensures a correct polar positioning. The MFU110WP rotary table is equipped with a quick clamping mechanism which allows a clamping disk exchange within seconds.

A major uncertainty source in earlier measurement procedures for piston-cylinder assemblies was the restricted reproducibility of the Z-position of the measurement, especially when moving the artefact from one measurement machine to another. The Z-component of the artefact coordinate system is of greater importance for the application, because piston-cylinder assemblies have to be paired for pressure measurement. The effective area has to be calculated for the paired system. An earlier approach for identifying the Z-position was based on the contacting of auxiliary spheres. But it was found that this approach was impractical and did not significantly improve the Z-position accuracy with respect to the standard procedure which identifies the edge of the front face of the cylinder by contacting.

4. CALIBRATION PROCEDURE PERFORMANCE TESTS

PTB has data records for certain piston-cylinder assemblies at its disposal which go back up to 20 years. During that time some assemblies were measured repeatedly by different machines and measurement procedures, including different error separation techniques. These artefacts are very well-known and consequently were selected to compare the results of the MFU110WP with those of the other machines. In addition, first measurement repeatability checks at the new artefacts were accomplished.

One of the piston-cylinder units with long measurement history is a 5 cm^2 unit identified by serial number 6222. It was used to study long-term stability and consistency between results of the new MFU110WP machine and those of other dimensional measurement instruments.

Other PCUs measured were 20 cm^2 units identified by the serial numbers 1159 and 1162, which were two of the six piston-cylinder assemblies to be used in the experiments for the re-determination of the Boltzmann constant.

The PCUs are made of a tungsten carbide material, each have a different design and were manufactured by DH-Budenberg, France (unit 6222) and by DH Instruments, USA (PCU 1159 and 1162), respectively.

4.1. Form measurements

Form measurements of known assemblies were repeatedly performed with the MFU110WP with both tactile and optical probing. The resulting data were analyzed with respect to noise, stability, reproducibility, and comparability to the historic data. It was found that optical contacting leads to the most stable results, at least under the high quality environmental conditions in which the machine is operated. Therefore, only the optical data are used for further discussion.

For comparability to historic data, all straightness profiles were filtered with a Gaussian low-pass filter with a 0.8 mm cut-off length. All roundness profiles were filtered with a low-pass, with a cut-off wavenumber of 150 UPR (the filters were implemented as described in DIN EN ISO 11562 [12]). The form profiles of common piston-cylinder assemblies generally don't carry significant harmonic content for cut-off lengths lower than 2.5 mm or wavenumbers greater than 50 UPR. Therefore, a stronger filtering could be applied without information loss. This might be an option for future data evaluations. The measurement uncertainty of form profiles is tightly connected to the filtering: Stronger filtering means lower uncertainty [13]. Here is a limited source, therefore, for uncertainty improvement.

Straightness comparison measurements of PCU 6222 showed that the reference tactile [14] and the optical probing method delivered undistinguishable results within the measurement uncertainty of 25 nm [19]. The same is true for the comparison of the reference roundness measurement method with the optical probing method.

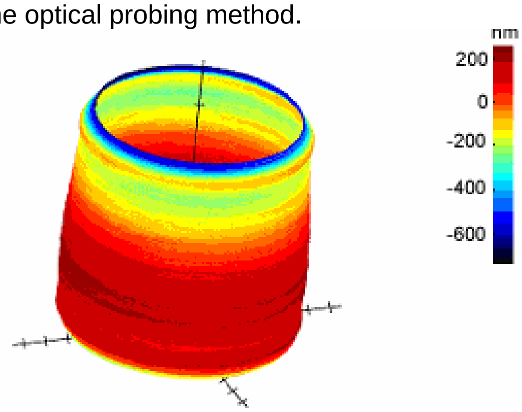

Fig. 2 *Helical scan of the full surface of a pressure gauge piston performed with the optical probe system.*

In fig. 2, a 3D representation of the piston PCU 6222 surface is shown. These data were gained by applying the MFU110WP optical helical scan mode. The data were not filtered, because so far there is no widely accepted or even standardized multi-dimensional filter algorithm available. In principle, data sets like this should be superior to line scans with respect to piston-cylinder calibration, because they carry topographic information about the full cylinder surface. However, so far there is no algorithm available to integrate the independently measured diameter information. Therefore, the directly measured full 3D data set can only be dealt with as additional information.

4.1. Diameter measurements and data evaluation

The three-dimensional data set was generated from the straightness (S), roundness (R), and diameter measurements (D) by a least-squares best-fit (LS) procedure [18]. All diameter results were taken into account. The fit procedure allows individual weighing of form and size data according to their uncertainties. However, for the actual evaluation, equal weights were chosen. The fit-procedure delivers a table of fit discrepancies, which can be used as a benchmark for the consistency of the input data. These typically amount to some single nanometers (e.g. 2 nm – 6 nm) [20]. They might be introduced e.g. by noise, time dependent artifact contamination, re-positioning inaccuracies and uncertainty of the measurement itself. Furthermore, a large local form deviation lowers the probability that the roundness and straightness profiles coincide perfectly at their cross points. The contacting of the diameter measurement is performed independently of the form measurement and therefore may be less reproducible in presence of large local form deviations. However, as piston-cylinder assemblies are high-precision cylinders, these effects tend to be small.
The resulting 3D data set was transformed into a coordinate system which coincides with the LS-cylinder axis. This step is important for the further virtual pairing of the piston and cylinder 3D data nets.
As an example, the results of piston cylinder unit (PCU) 1159 are discussed. The straightness deviations of 1159 amount to approx. 0.5 µm along the whole piston length and only 0.1 µm along the piston-cylinder coupling length which is relevant for the effective area calculation. The roundness deviations amount to approx. 60 nm. Fig. 3 shows a 3D visualization of the linked 3D data net. Visualizations like this can be used as an alternative tool for identifying fit-discrepancies. Following [20], and [21] the corresponding measurement uncertainties for the 3D data sets range from 7 nm (outer cylinder) to 15 nm (inner cylinder).

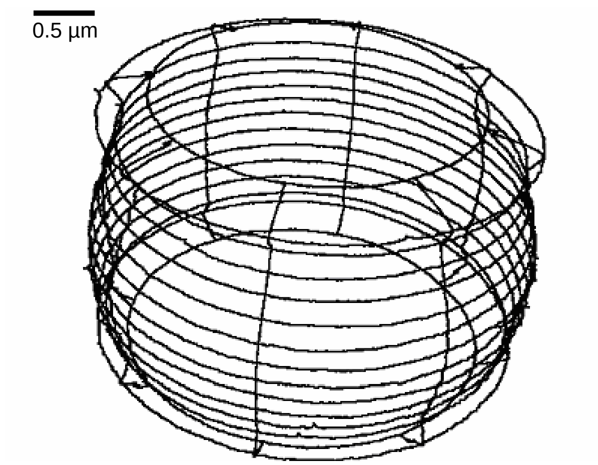

Fig. 3 *Visualization of the 3D data set of the PCU 1159 piston*

5. CONCLUSIONS

It was shown that three-dimensional calibrations of piston-cylinder assemblies can be performed with standard measurement uncertainties below 20 nm. It provides an important precondition for a successful re-determination of the Boltzmann constant by the DCGT method from dimensional metrology point-of-view. Further work will concentrate on the generation of 3D data from optical helical traces and the comparability of dimensionally evaluated effective area ratios between PCU pairs to data determined directly via pressure cross-float measurements.

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