IMPROVED TECHNICAL IMPLEMENTATION OF AN EXTENDED REVERSAL CALIBRATION PROCEDURE FOR CYLINDERS

Otto Jusko, Heinz Lüllmann, Michael Neugebauer, Helge Reimann

Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany, otto.jusko@ptb.de

Abstract: It is well-known that the uncertainty of the straightness, parallelism and squareness calibration of cylindrical parts can be improved by using error separation techniques like reversal methods. An extended procedure of this class which utilizes laser-interferometry has been implemented. The improvements in comparison with earlier implementations include an ultra-light multipurpose probe support system made from CFRP with custom-made attachable probe systems, an optimized interferometer control, and a complete technical refurbishment of the utilized form measurement machine.

Key words: reversal method, CFRP probe, flexural pivot

1. INTRODUCTION

Cylindrical geometry is the dominating shape of most high-precision industrially manufactured parts. The same is true for many embodied standards in metrology. Important examples are piston cylinder assemblies used in piston manometers [1]. Whereas the of roundness calibration of cylindrical parts can be easily performed with uncertainties far below 0.1 µm without greater effort, the calibration of straightness, squareness, and especially parallelism suffers from many limitations of existing form measurement machines. These include guide deviations and parallelism deviations of C- (i. e. rotary) and Z-axis of the form tester. Therefore, the achievable uncertainties often amount to 0.5 µm or more.

2. ERROR SEPARATION BY EXTENDED REVERSAL

The uncertainty of these procedures can be improved by error separation procedures like e. g. reversal methods [2]. In case of straightness and/or parallelism calibrations this means that the same generatrix of cylinders has to be scanned in two opposing orientations of the rotary table in the X-Z plane. A prerequisite of all error separation procedures is the reproducibility of the guide profiles. Both scans of a reversal procedure must contain the same guide profile, but with opposing sign. However, many form measurement machines have to move parts of larger mass, like e .g. the Z-axis tower, to move the probe system from one generatrix to the other. This leads to parallelism changes of Z- and C-axis. In effect, the prerequisite for error separation procedure is violated. The Mahr MarForm MFU 8/800 family consists from machines of this class. Therefore an enhanced reversal procedure for this machine class was developed and already described elsewhere [4]. It is based on a large plane-mirror (#5 in fig. 1) which is probed by laser interferometry during tactile probing and scanning of a cylindrical part. By taking the mirror profile into account, the calculation of the reversal profile can be corrected for angular errors resulting from the machine deforming caused by the changing position of the Z-tower during the procedure. An important pre-requisite for this procedure is the spatial invariance of the parallelism of the plane-mirror to the rotary axis.

Ref. [4] is not easily available. Therefore, it was decided to derivate the main equations again for this paper.

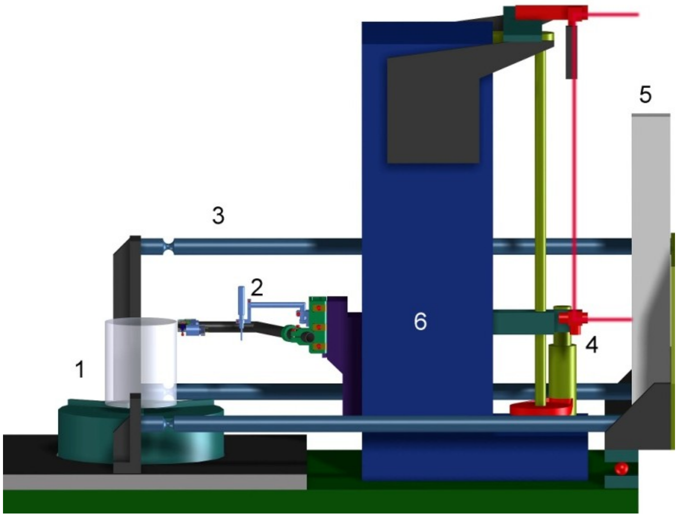

Fig. 1. MFU8PTB Retrofit measurement machine, 1: rotary table and cylinder, 2: probe support with probes, 3: rods with flexure hinges, 4: laser interferometer, 5: plane mirror, 6: Z-Tower with Z-Guide

For the reversal procedure the generatrices of the cylinder under test were scanned in two different positions each. One is near to the Z-tower and one is on the other side of the artifact. The generatrix was positioned by the rotary table. (measurement profiles T and T^*). This could only be realized when the probe was able to touch the same generatrix in both orientations. Therefore a special geometry constraint of the probe support had to be obeyed. The probe and the laser interferometer signals (L and L^*) were read simultaneously.

With:

S_F: form profile of mirror (best-fit line subtracted)

S_w: angle of mirror profile (best-fit line)

Z_F: form profile of Z-guide

Z_w: angle of Z-guide

M_F: form profile of cylinder generatrix

M_w: angle of cylinder generatrix

The following is valid:

Laser measurements:

$$L = – S_W – S_F – Z_W + Z_F$$

$$L^* = – S_W – S_F – Z_W^* + Z_F$$

Probe measurements:

$$T = – M_W + M_F + Z_W – Z_F$$

$$T^* = – M_W + M_F - Z_W^* + Z_F$$

These basic equations allow to deduce the following relations:

Deviation from straightness of the individual generatrix:

$$M_F = ((T^* + T) – (L^* – L)/2 -M_W$$

Deviation from squareness to the base:

$$M_W = (- (T^* + T) + (L^* - L) + 2 M_F) / 2$$

If the base plate is not perfectly adjusted to the C-axis a further correction has to be applied, which can be calculated by taking into account the apparent eccentricity E_x of a run-out measurement of the base plate and the radius R where the run-out was scanned.

$$\Delta M_W = E_x/2 * R$$

Recently, many enhancements and technical changes for the measurement equipment were implemented which are described in the following.

3. 1D-PROBE WITH FLEXURAL PIVOT

As commercial probe systems were found to be too inflexible and limited in many ways for the foreseen purposes, like e. g. regarding the selection of spring constants and probe geometries, a custom-made family of probe systems was developed. Its key components are commercially available flexural pivots (Fig. 2). These are mechanical systems which combine crossed springs in a common housing. The spring constant of the system can be chosen within wide limits (e.g. 0.1 Ncm/rad … 4000 Ncm / rad). Generally, we choose the spring constant with the aim to achieve probing forces of some mN. The probe shaft is attached to the flexural pivot and carries the probing element and a core which acts as moving component of a LVDT system.

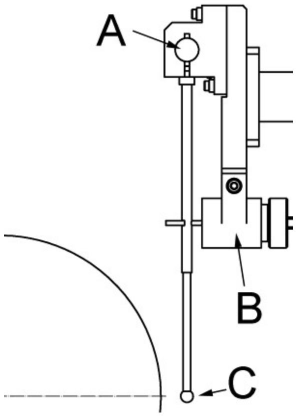

Fig. 2. 1D-probe (A: flexural pivot, B: housing of LVDT, C: probing element)

4. DIAMOND PROBES

It was found that the stability, reproducibility, and wear effects of form scans can be significantly improved by utilizing probing spheres made from single diamonds. Therefore it was decided to prefer this probe material for the application in error separation procedures, where the probe diameter is available. A possible alternative to full material diamond probes are diamond layered probes, which just have become available on the market.

5. MFU 8 REFURBISHMENT (“RETROFIT”)

The form measurement instrument which was used for the earlier implementation of the reversal procedure [4] was a modified MFU 8 machine, which was in service since 1989. In the meantime various parts began to show performance degradation and the service of the control electronics was abandoned. Therefore it was decided to refurbish the machine completely with the help of the manufacturer. Where the air-bearings and most basic mechanical parts of the machine still remained the same, all electrical and electronic parts were modernized. This “retrofit” procedure included exchange of the scales, motion control, and drives. The new version can be called the MFU8PTB Retrofit.

The resulting machine status now is completely hard- and software compatible with current form measurement machines of manufacturer Mahr. The software base is now MarWin with extensions made in PTB.

Some of these extensions were implemented for realization of the communication link between the Mahr system and the external Zygo heterodyne laser-interferometer system. The stability of the length measurement system already was found to be sufficient for uncertainties in the sub 0.1 µm regime.

6. ULTRA-LIGHT PROBE SUPPORT

As a side-effect of the exchange of the motion control also the Y-axis had to be exchanged. However, the new one is not able to carry as much load as the old version. Consequently, the former probe system, which was used for reversal procedures, could not be used anymore.

To re-implement the reversal measurement capabilities a new probe support was designed. Its mass was minimized by using CFRP (carbon fiber reinforced plastics) for the main probe arm. Further mass reduction was achieved by optimization of the support arm geometry.

One design goal of the system was versatility i. e. several probe arms carrying various probes can be attached to different positions of the support (Fig. 3). Some of them are also capable to be operated in parallel enabling multi-probe procedures or an easy switch between probes touching different surfaces of the work-piece e. g. front face and barrel of a cylinder. That operation mode would supersede the need for a reference base plate for orientation of the cylinder.

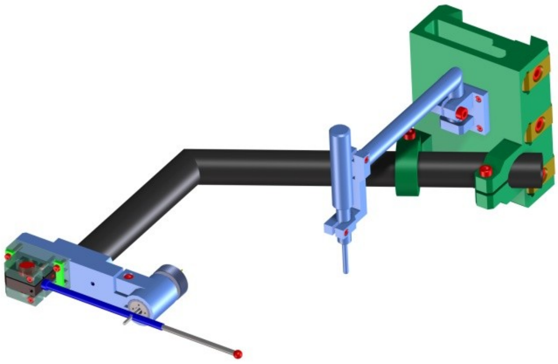

Fig. 3. Probe support with two arms and probes attached. The main support arm is made from CFRP.

7. RESULTS

Only some first measurements could be performed using the new system. The system was able to achieve satisfying data under stable environmental conditions. An example of the two sets of raw data scans of the four major generatrices of a reference cylinder is demonstrated in fig. 4. The cylinder has straightness deviations of only 0.08 µm to 0.16 µm. It is obvious that the apparent direction of the generatrices and thus the uncorrected parallelism values differs significantly and is much too large (> 1µm) for a reference cylinder. After calculating the resulting reversal data set, the parallelism is corrected to 0.16 µm (0°/180°) and 0.14 µm (90°/270°). The effect to the straightness deviation itself can be neglected (fig. 5). This is a consequence of the very good and reproducible Z-guide of the MFU8 machine.

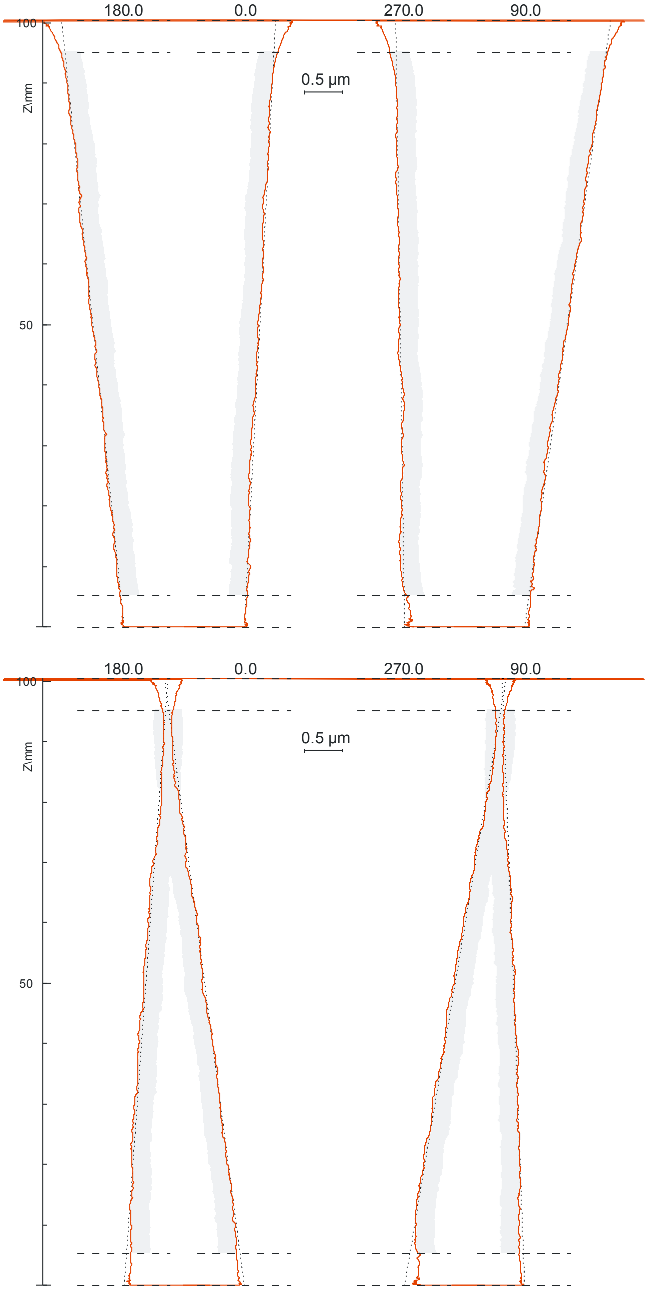

Fig. 4. Reversal procedure raw data.

(a) Upper graph: Four straightness measurements with the probe in the position near to Z-tower.

(b) Lower graph: Measurement of the same generatrices at the position far from the Z-tower.

It is too early to determine the long-term reproducibility and achievable measurement uncertainty of the procedure. However, it was found casually that the probe system incl. the CFRP support showed drift effects. This means that small changes of the environmental conditions had quite significant influence to the probe read-outs (fig. 6) and such to the resulting angle and form values of the reversal procedure. In effect, the target uncertainties of 0.08 µm for the straightness and 0.15 µm for the parallelism deviation could not be achieve, but not in all runs.

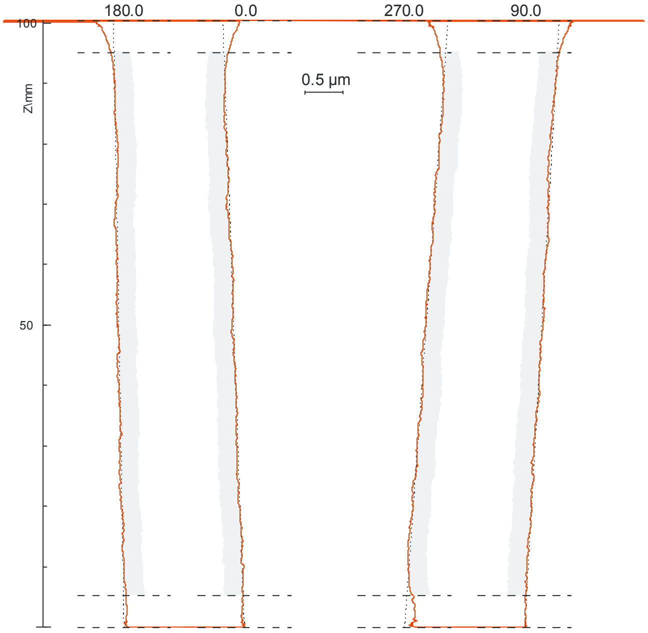

Fig. 5. **Result of reversal procedure. The parallelism is corrected. The straightness is only influenced slightly.**

A possible source for this instability may be the bonded joint at the kink of the CFRP probe support. To differentiate influences from the probe support construction, the probe stability was tested independently by using a massive INVAR support. In this configuration a much better stability could be realized (fig. 7). This cannot be explained by thermal expansion coefficients (CTE), because the CFRP should be at least as thermally invariant at 20°C as INVAR. Moisture influences the mechanical stability of CFRP [5]. However, the experiments were made within an air-conditioned room with relative humidity changes of only some few %.

It was found that the CFRP support caused some of the instability problems, but not all. Therefore, the probe system itself will also be further examined regarding mechanical problems.

A new CFRP support will be designed. In the meantime the INVAR support will be utilized. It is assumed that more stable data can be presented at the CIMMEC conference.

The finally achievable measurement uncertainty is assumed to be lower than in the earlier realization of the reversal procedure. One supporting argument is the higher measurement speed which allows to minimize drift within the machine and makes the machine less dependent from long-term temperature variations of the air-condition. Additionally, the laser read-out was optimized which enables more data averaging than before.

ACKNOWLEDGMENTS

Many thanks to Waldemar Kirst for preparing the CAD images.

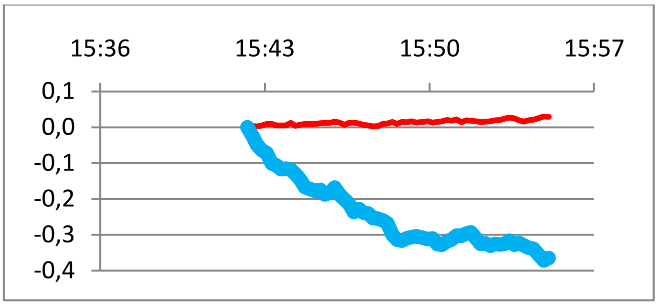

Fig. 6. **Stability test of the CFRP support: Red: laser read-out in µm), Blue: probe read-out. The probe shows a significant drift within a 20 min. period. Horizontal axis is absolute time.**

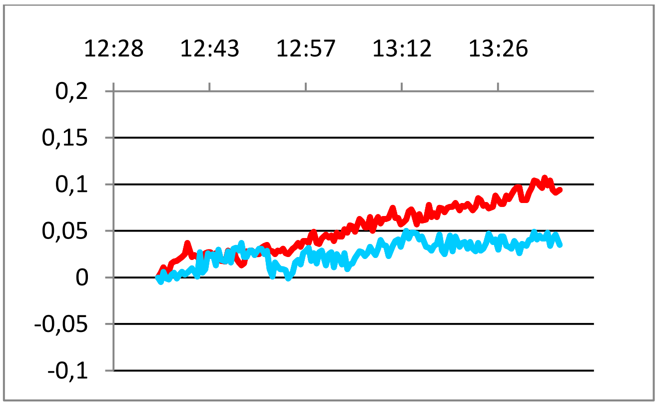

Fig. 7. **Stability test with INVAR support: Red: laser read-out in µm), Blue: probe read-out. The stability of the INVAR support is much better than that of the current CFRP support. Horizontal axis is absolute time.**

REFERENCES

[1] Jusko, O, Bastam, D; Neugebauer, M; Reimann, H; Sabuga, W; Priurenrom, T, Final Results of the Geometrical Calibration of the Pressure Balances to be used for the new Determination of the Boltzmann Constant, Key Engineering Materials, Vol. 437, 2010, p.150-154, doi:10.4028/www.scientific.net/KEM.437.150

[2] Evans C J, Hocken R J, Tyler Estler W: Self-calibration: reversal, redundancy, error separation, and "absolute testing". Annals of the CIRP Vol. 45/2/1996, 617-634

[3] Lüdicke F, Jusko O, Reimann H: Form and length measurements using a modified commercial form measuring instrument. Proceedings of the ASPE 15th Annual Meeting, Scottsdale (Arizona), October 22nd - 27th 2000, ISBN 1-887706-24-0, 389-392

[4] Jusko, O., Neugebauer, M., Reimann, H., High-Precision dimensional calibration of reference cylinders, Proc. Congress on Metrology, Measurement & Instrument Technology, IMEKO TC 14, 2001, I-7ff.

[5] Abusafieh, A., Federico, D., Connell, Cohen, E. J., and Willis, P. b., Dimensional Stability of CFRP Composites for Space Based Reflectors, trs-new.jpl.nasa.gov/dspace/bitstream/2014/13192/1/01-1872.pdf