Traceable measurement of large gears with micron accuracy

A mandatory basis for reliable wind energy systems

F. Balzer[1], N. Steffens[1], M. Stein[2], K. Kniel[2]

[1] Hexagon Metrology GmbH, Siegmund-Hiepe-Str. 2-12, D-35578 Wetzlar
[2] Physikalisch-Technische Bundesanstalt, Bundesallee 100, D-38116 Braunschweig

ABSTRACT

The production of highly accurate components of renewable energy systems such as Wind Energy Systems (WES) or Tidal Power Generators (TPG) puts mandatory constraints in the verification procedures related to 3-D geometry for the tolerance of size, form, waviness and roughness. More information concerning geometric flank deviations, the case hardening and surface roughness properties are requested.
This paper focuses on the calibration and measurement of large gears used in gearboxes of WES and TPG. One major issue ensuring traceability of these measurements is the lack of appropriate gear measurement standards. One large ring gear measurement standard was developed recently by the Physikalisch-Technische Bundesanstalt (PTB). In this contribution, the ring gear and its calibration on a large coordinate measurement machine (CMM) are described. Tactile measurement results are presented and put into context with calibration values from PTB. Furthermore, optical measurement results using a new interferometric point sensor, developed by Hexagon, are presented.

Index Terms **–** Renewable energy system, large ring gear measurement standard, M3D3 calibration, optical gear measurements

1. INTRODUCTION

The production of highly accurate components of renewable energy systems such as Wind Energy Systems (WES) or Tidal Power Generators (TPG) in a globalized industrial manufacturing environment strongly involves a need for appropriate coordinate measuring machines (CMMs) as well as a necessity for traceability of these measurements. This requires the full adoption of well harmonized international standards dealing with specification and verification procedures to be reported in the manufacturing documents. The main reason is, that WES and TPG are regarded as promising technologies but reliability still needs to be improved, as they rarely reach the desired lifetime of 20 years without at least two mechanical failures of major drivetrain components [1]. These failures in the powertrain mechanical system can lead to downtimes of several weeks and may have dramatic costs for accessibility issues, operations in difficult conditions, and loss of power generation.
The required reliability for powertrain components on renewable energy systems puts mandatory constraints in the verification procedures related to 3-D geometry for the tolerance of size, form, waviness and roughness. One major issue ensuring traceability of these measurements is the lack of appropriate gear measurement standards. More information concerning geometric flank deviations, the case hardening and surface roughness properties are

requested. These extensive measurement tasks with the aim of characterizing large gears as complete as possible come into conflict with the need for short measuring times.

In this paper, challenges of large gear measurements in industry are described first. Afterwards a recently developed large ring gear measurement standard by PTB and its calibration using the M3D3 method on a large CMM are presented. Tactile measurement results are shown and put into context with the calibration values. Furthermore, optical measurement results using a new interferometric point sensor, developed by Hexagon, are presented.

2. CHALLENGES OF LARGE GEAR MEASUREMENTS

In general, there are growing inspection demands for the measurement of large gears (i.e. for wind turbine applications), which differ from the requirements known for smaller gears (i.e. automotive applications). This is mainly caused by the different production processes [2]. Smaller automotive gears are often completely machined in less than one minute. This enables huge quantities per year. In contrast, production processes for large gears consist of more steps and can last several hours. The heat induced in the part, the temperature behaviour of the production machine and tool wear differ fundamentally. For small gears, the heat induced is minimal and almost symmetric. Due to the short cycle time tool wear and thermal drift of the production machine can be neglected when considering a single part. In contrast, for large gears the latter two factors must be considered during production processes as well as in the measurement strategy during quality control. In addition, the production processes are often characterised by a non-symmetric heat induced in the part due to other milling or grinding strategies. Thus, it cannot be assumed that all teeth nearly have the same shape and surface characteristics.

Considering quality control, large gear measurements face a lot of challenges regarding the mounting of the part to minimise deformations due to the weight of the part and regarding the available CMMs and their properties. One main obvious difference comparing CMMs for small and large gear measurements is the measurement uncertainty. Today geometric measurements of large gears normally cover the same measurement quantities compared to smaller gears used in the automotive sector. This means, profile and helix deviations are characterised at some equally distributed teeth using one measurement line at each flank. In addition, pitch and run-out are measured. However, taking into account the production history of the parts, the inspection requests for large gears have to be adapted. This means, that almost all teeth have to be measured across the complete surface with several measurement lines on each flank. Furthermore, due to the fact that the materials for gear manufacturing are becoming better, information about the surface characteristics, the near-surface layer and surface roughness properties are becoming important for quality inspection, too. These extensive measurement tasks with the aim of characterising large gears as complete as possible come into conflict with the need for short measuring times. The latter are necessary due to several aspects. The economic issues are throughput and cost efficiency since large CMMs are expensive and therefore normally operated at almost full capacity. Technical issues are the reduction of thermal drift of the part and temperature behaviour of the CMM that may influence the measurement results [3].

Another aspect, regarding the traceability of the measurements, is the lack of appropriate calibrated master gears for large gears. This is of interest because the manufacturing tolerances – in particular for large parts – are increasingly smaller. The accuracy of current standards often does not meet the requirements for checking these tolerances any more.

3. NOVEL LARGE RING GEAR MEASUREMENT STANDARD

To overcome the lack of appropriate large master gears a novel large ring gear measurement standard and an appropriate universal supporting base for use on CMMs and gear measurement machines (GMMs) have been developed by PTB in context of a German research project EVeQT [4] between Bremen Institute for Metrology, Automation and Quality Science (BIMAQ), PTB and Hexagon Metrology GmbH. The gear ring embodies three different internal and external gears, equally distributed on the circumference of the ring (see Figure 1). It has an external diameter of 1980 mm and its weight amounts to 2.7 t [5].

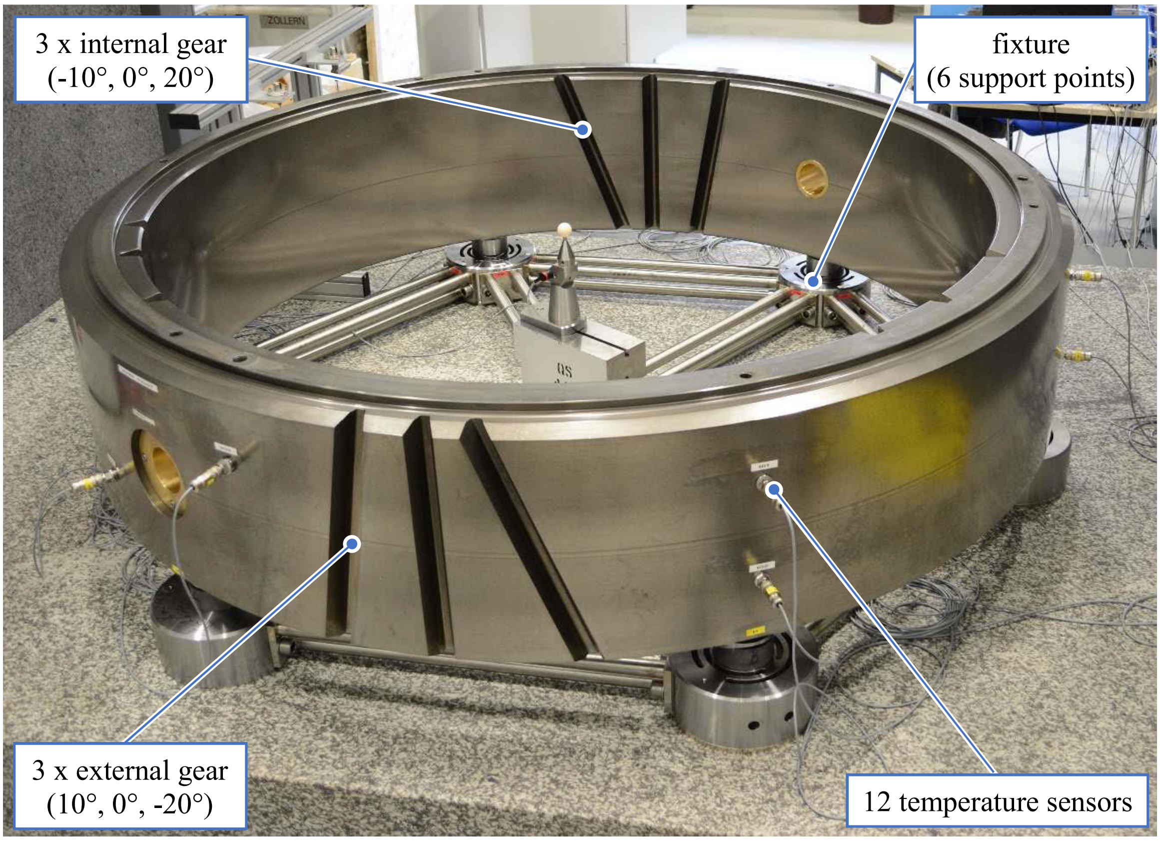

Figure 1: Large ring gear measurement standard from PTB

The three external gears as well as the internal gears have helix angles of 0°, 10° and 20°. The external gears have a face width of 420 mm, whereas the internal gears have a face width of 424 mm [5]. Furthermore, the ring gear standard includes 12 boreholes for Pt100 temperature sensors to monitor, investigate and/or compensate the temperature distribution inside the work piece.

The large gear ring measurement standard has a supporting base specifically designed and manufactured at PTB with six supporting points. One of the supporting points is fixed. The others show three degrees of freedom. Three rotational movements around x-, y- and z-axis are allowed. The total weight of the base amounts to 0.4 t [5].

4. CALIBRATION OF THE LARGE RING GEAR MEASUREMENT STANDARD

4.1 Calibration method

For calibration of the large ring gear measurement standard a novel calibration method developed by PTB [6] for calibration of large parts directly on-site in production was used. The calibration method is called “mobile measuring machine for 3-dimensional measurements” (M3D3) and is based on multi-lateration using at least four portable tracking laser interferometers called LaserTracer [7]. Furthermore, a commercial CMM and its measurement and evaluation software are necessary. The M3D3 method combines tactile probing on a CMM and an optical measurement with the LaserTracers yielding a task-specific error correction and estimation of measurement uncertainty.

The CMM is used as a mover which allows to capture points on the surface of a measuring object. In this case it is the large ring gear measurement standard. Within the measurement volume of the CMM the four LaserTracers are aligned in non-coplanar condition. At least four of them are required to determine the unknown dead path of each of the interferometers [6]. This alignment is one of the main challenges for real parts because the visibility of the retro-reflector for all LaserTracers has to be guaranteed simultaneously. That is why in practical the M3D3 method is split into two measurement tasks and a following offline evaluation. The first measurement task is the conventional tactile gear measurement during which all of the measured points on the surface have to be stored in CMM’s global coordinate system (see Figure 2).

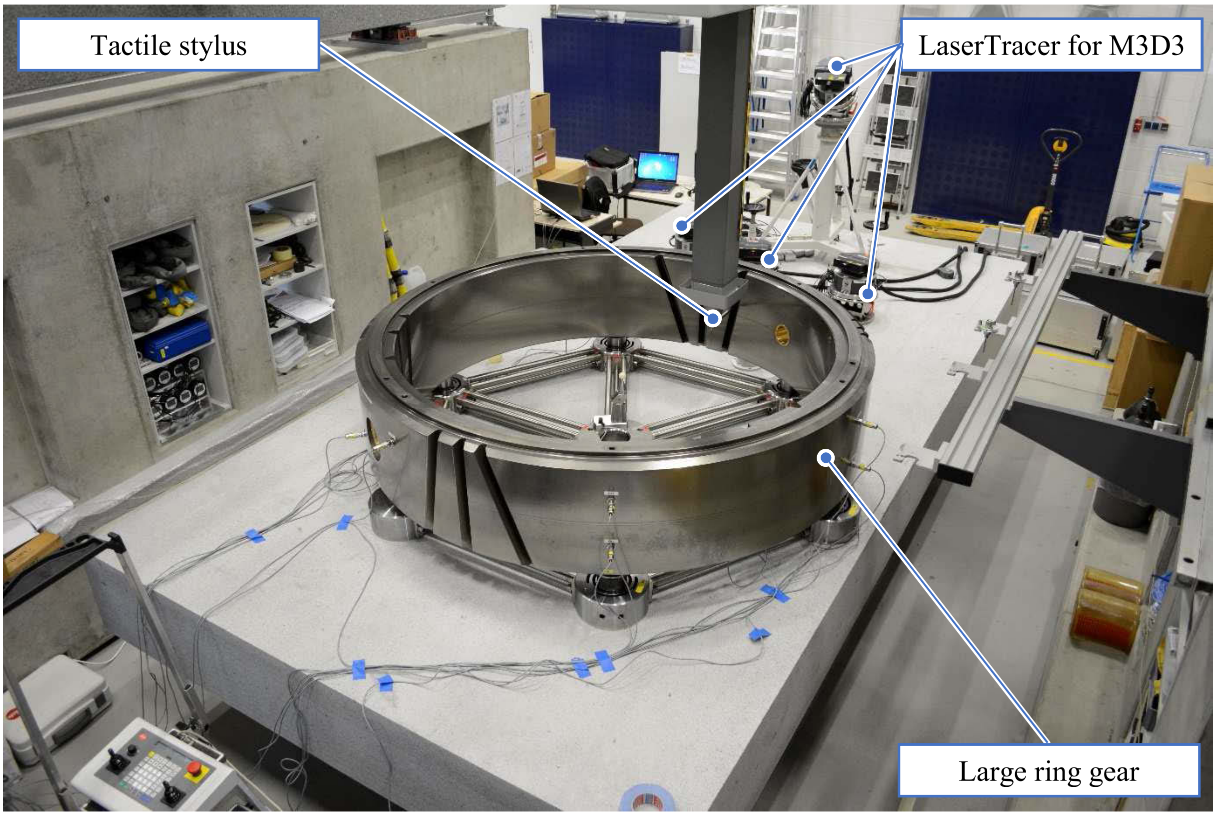

Figure 2: Tactile gear measurement for the M3D3 calibration on a Hexagon Leitz PMM-G

After the tactile measurement, the large ring gear is removed and the tactile stylus is replaced by the retroreflector. Then all previously saved probing points are replayed exactly. At each probing point the CMMs position as well as the length value of each LaserTracer are saved simultaneously (see Figure 3). Based on the principle of multi-lateration, the 3D point coordinates x_i, y_i and z_i of the LaserTracer measurement are calculated by using the measured length changes l_{ij}' [8]:

$$l_{ij} + l_{0j} + w_{ij} = s_j\sqrt{\left(x_i - x_{0j}\right)^2 + \left(y_i - y_{0j}\right)^2 + \left(z_i - z_{0j}\right)^2} \qquad \text{(Eq. 1)}$$

In equation 1 $i = 1 \dots n$ is the measurement point number, $j = 1 \dots m$ the LaserTracer position number ($m \geq 4$), x_i, y_i, z_i the coordinates of measurement points (unknown), x_{0j}, y_{0j}, z_{0j} the coordinates of LaserTracer positions (unknown), l_{0j} the unknown dead path length of LaserTracer j, s_j the scale factor from calibration of LaserTracer j, l_{ij} the measured length change from LaserTracer j to point i, and w_{ij} the residual between measured and fitted distance to measurement point. In practice, when executing a typical calibration task with several hundred measurement points, there is a set of equations yielding an over-determined equations system. The solution of this over-determined equations system is described in [8] in detail.

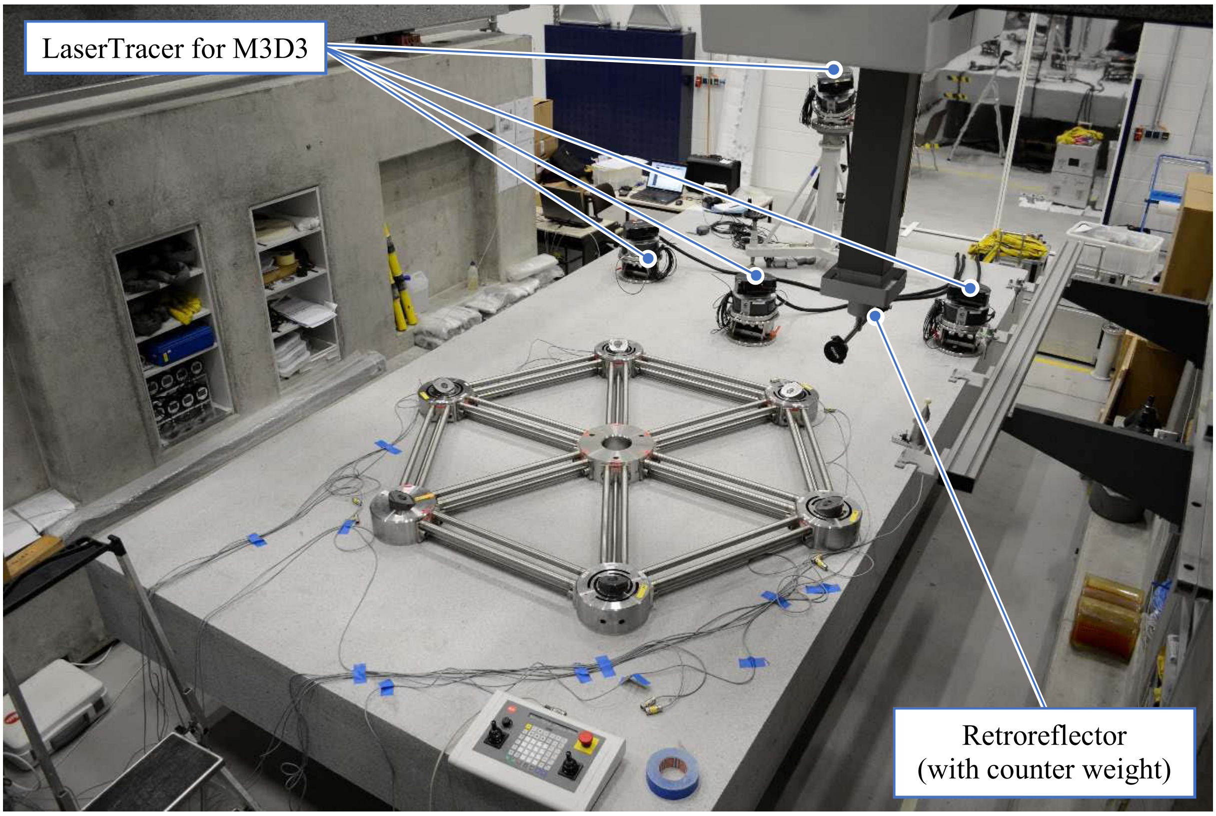

Figure 3: Optical measurement for the M3D3 calibration using four LaserTracers

After solving this equation system according to the description in [8] a local error vector at each probing point is calculated from the difference between the indicated CMM stylus position and the position measured with the M3D3 system. Since this local error vector is given for each measuring point, no specific geometric model of the CMM is required for error correction [6]. As stated in [6], this is one of the main advantages in comparison with the parametric error compensation approach described in [9].
All originally tactile measured points are corrected using the error vector calculated by the M3D3 method. Afterwards these corrected points are used for re-evaluation of the gear parameters within the CMM measurement and evaluation software QUINDOS.

4.2 Calibrated parameters

The calibration of the large ring gear measurement standard has been conducted by PTB using the M3D3 method on a commercial Hexagon CMM of type Leitz PMM-G in combination with the measurement and evaluation software QUINDOS. This CMM type shows repeatable systematic deviations which is one of the main requirements for applying M3D3 method.
Using the M3D3 method six external and six internal gear flanks have been calibrated according to existing standards and guidelines (e.g. ISO 1328-1 [10]) using one profile and one helix line per flank. For all the profiles the slope deviation $f_{H\alpha}$, the form deviation $f_{f\alpha}$ and the total deviation F_{α} have been evaluated. Equivalently, the helices are calibrated in terms of $f_{H\beta}$, $f_{f\beta}$ and F_{β}. In total, there are 72 calibrated parameters describing the large ring gear measurement standard. The resulting calibration values have been determined with expanded measurement uncertainties smaller than 3.5 µm for all gear parameters [11].

5. INTERFEROMETRIC POINT SENSOR

5.1 Motivation for optical measurements

In a national intercomparison the large ring gear measurement standard has been measured by seven participants on twelve different machines with tactile sensors using single points. Among the participants were CMM manufacturers, GMM manufacturers, laboratories for calibration services and research institutes. The results have been compared to the calibrated values. Except a few outliers most of the results are within the uncertainty ranges [11]. Figure 4 shows the anonymized results of all participants of the profile measurements for the external gears as an example. The error bars visualize the expanded measurement uncertainties U95% = U(k=2) determined by PTB with M3D3 calibration method.

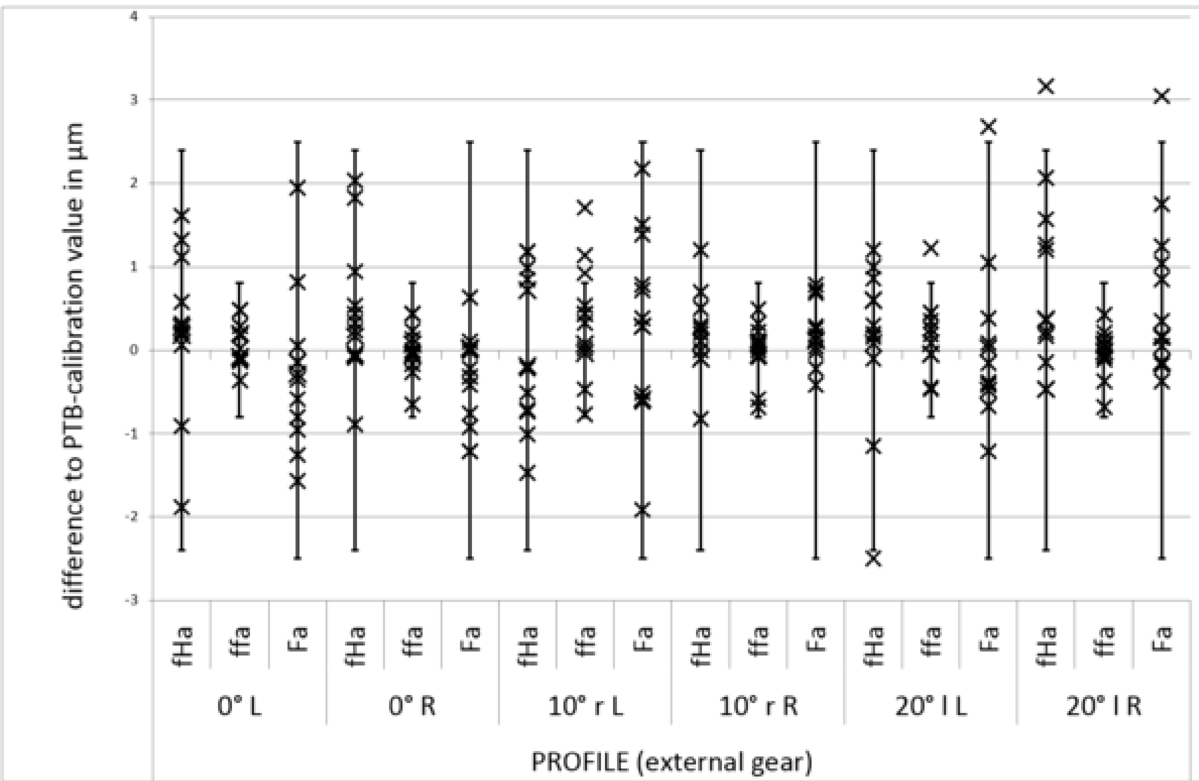

Figure 4: Results of profile measurements for the external gears [11]

In industrial practice, geometric deviations of gears are usually not characterized by single point measurements as in the intercomparison. Instead most of measurement points are covered by scanning the surface. This is not thus time-consuming. But as described in chapter 2, one profile and one helix line may not be sufficient for characterising geometric deviations of large gear flanks. That is why an ongoing trend can be observed in industry to measure more profiles or helices on one flank. This is costly in terms of time because large CMMs have a limited dynamic behaviour. One approach for overcoming this lack of dynamics is measuring non-tactile with optical sensors.

5.2 Functional principle

Hexagon developed an optical laser interferometric point sensor (1-D) called HP-O, which is designed as a new scanning technology on stationary CMMs [12]. The HP-O consists of an optical probe head (OPH), connected to the CMM probe head as shown in Fig. 1, and an optical probe controller (OPC). Both units are connected by a single optical fibre (see Figure 5).

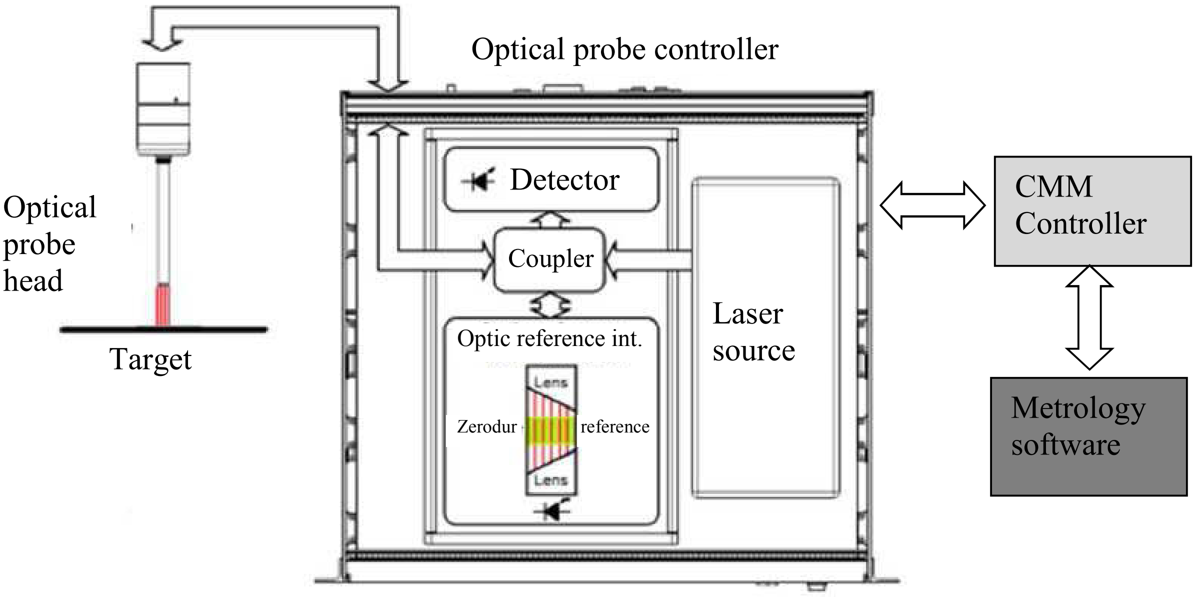

Figure 5: Working principle of the complete optical probe system (in dependence on [12])

The OPC is usually placed near the CMM controller preventing waste heat from influencing the CMM's measurement set-up. The OPH can be exchanged to adapt to the requirements of the gear measurements. The standard probes can be ordered with several working distances (6.5 mm, 10.5 mm and 16 mm) as well as various beam exit angles (0°, 30°, 45° and 90°).
The functional principle of the interferometric probe system is based on frequency modulation. The laser light emitted from the laser light source in the OPC is coupled into the OPH using an optical fibre. Inside the OPH there is a micro-optics system with a partially reflective surface acting as a reference (Fig. 3), generating the first light wave (reference beam) utilising one portion of the laser light. The other part is sent through a focussing lens into the direction of the work piece (target). If the target is in focus, a second light wave is generated as a reflex from the target's surface (measurement beam) and coupled back into the OPH using the same optical system. Due to the propagation time of the second light wave and the continuous change of the laser wavelength a slight difference in the optical wavelength appears between the reference and the measurement beam causing a periodic signal (interferogram).

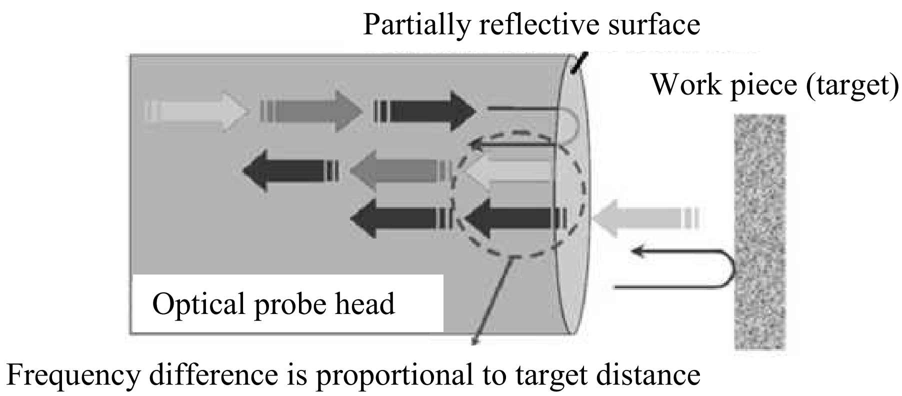

Figure 6: Functional principle of the interference generation (in dependence on [12])

The interferogram is evaluated in the OPC's detector to derive the distance information. In the OPC the laser light emitted by the laser source is sent to an optic reference interferometer additionally, before it is coupled into the OPH. This reference interferometer is necessary for a distance reference (i.e. in the case, that the optical sensor loses work piece contact) and to compensate non-linearities as well as temperature effects.

6. APPLICATION OF THIS OPTICAL SENSOR FOR LARGE GEAR MEASUREMENTS

6.1 The difference between tactile and optical gear measurements

Tactile gear measurements on CMMs are state-of-art for decades. It is a well-known technology and the calculation algorithms in the metrology software as well as the online correction algorithms in the CMM controller are very sophisticated. However, gear measurements with optical sensors are completely different. Optical sensors suitable for geometric measurements can be 1-D (point sensors), 2-D (line sensors) or 2.5-D (area-oriented sensors). In any case there is no direct information about the surface's normal vector for each probing point. This requires the measurement strategy and in some cases the evaluation algorithms to be changed, too, because for conventional tactile measurements information of the surface normal vector is gained from the probe head deflection.

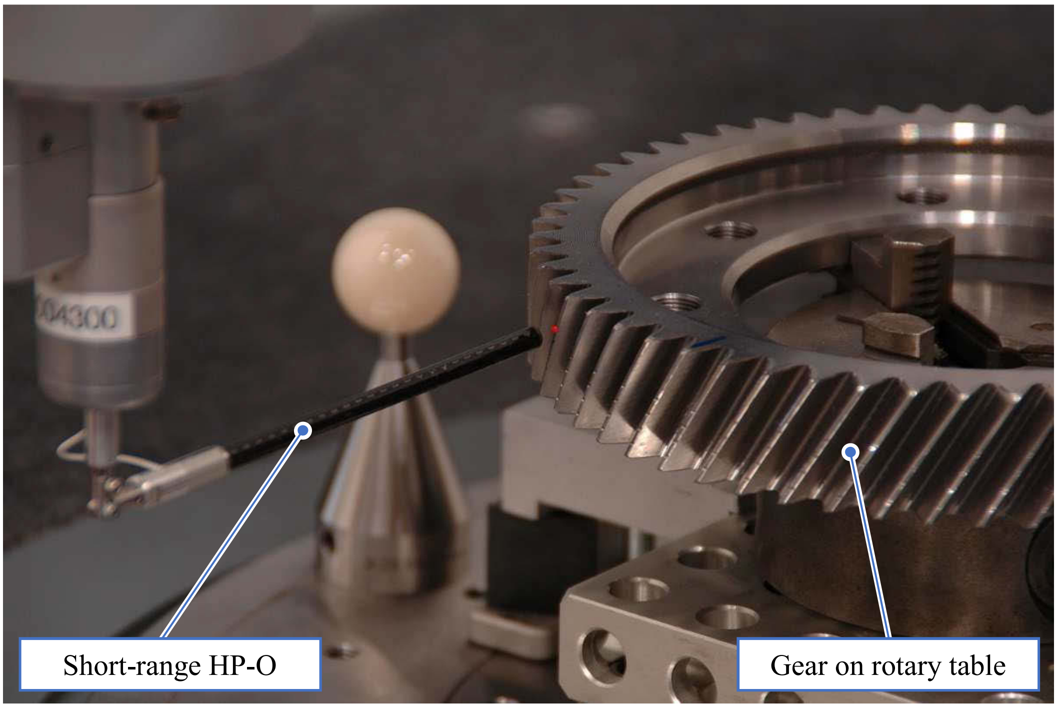

Figure 7: Exemplary gear measurement with HP-O

Other main influence factors, i.e. the acceptance angle and the working distance of the optical sensor, have to be taken into account for the new optical measurement strategies. The fact that these parameters cannot be assumed to be constant during practical measurements, because they are also dependent from the surface quality of the gear, is a big issue. Additionally, the new evaluation strategies for gear measurements have to take care of outliers that cannot be avoided if optical sensors are used. Furthermore, they have to deal with missing points and in some cases a higher point density.

6.2 Preliminary investigations into optical gear measurements

For the investigation of gear measurement capability using optical sensors some small gears have been chosen. The main reason is the easier handling on the CMM and that they have an official certificate. Namely, the test gears have been high quality Identical Condition (IC) artefacts according to ISO 15530 [13] and in addition a gear with modifications on several teeth provided by PTB.

In these preliminary investigations the wide variety of HP-O probes was evaluated to judge their capability for gear measurements. At first, there is a requirement regarding the CMM. For gear measurements with HP-O sensor the CMM must be equipped with an additional rotary axis, since the optical probes have a fixed measurement direction (see Figure 6). Consequently, the rotary axis is then necessary to guarantee accessibility for the optical sensor. This rotary axis can be an indexing head or a rotary table. A rotary table is preferable because it allows full four axes scanning with continuous rotary movement.

Due to the high acceptance angle of the HP-O, which is necessary to be able to start i.e. profile measurements near the root of the tooth, only the optical probes with a short working distance (approximately 6.5 mm) or medium working distance (approximately 10.5 mm) and a high acceptance angle (approximately ± 30° for rough surfaces) are suitable.

In another investigation the accessibility of the gaps using several probes with different exit angles of the laser beam was examined. In a first step, some simulations have been done to investigate the relationship between gap width and acceptance angle (see Figure 8). In a second step, these simulations have been verified by measurements with HP-O on real-world gears.

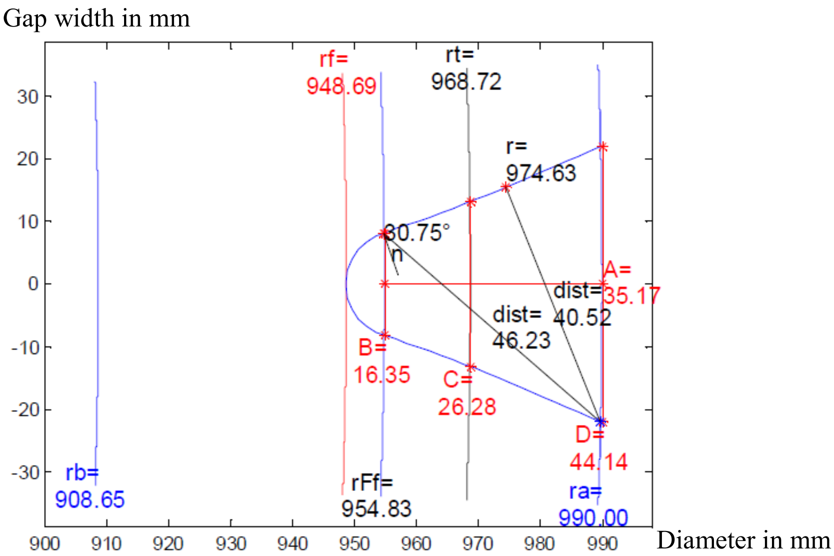

Figure 8: Calculation of gap width for large ring gear measurement standard to investigate acceptance angle of HP-O [3]

In conclusion, for smaller gears the optical probe with 0° exit angle showed the best measurement results and guarantees the maximum diversity of gears that can be measured. For larger gears additionally an optical probe with 45° exit angle comes into consideration. But it has to be taken into account, that two probes on different stylus holders are needed in that case to access left and right flanks of the gear.

7. COMPARISON BETWEEN TACTILE AND OPTICAL MEASUREMENT RESULTS OF LARGE RING GEAR MEASUREMENT STANDARD

The preliminary investigations and the theoretical simulations have shown that the HP-O is suitable for measuring the large ring gear measurement standard. In context of the national intercomparison the artefact was measured on two devices at Hexagon in Wetzlar with single points. All of the results lie within the uncertainty ranges of PTB.
For the comparison between tactile and optical measurements only scanning measurements are used. That is why in a first step the scanning capability was compared to single point measurement. A CMM of type PMM-F was used for these investigations. Different scanning speeds have been tested to see the limitations of the CMMs dynamic behaviour. For each scanning speed a set of 10 repetitions was executed. For a more meaningful comparison between both point acquisition types, no filter was applied in the metrology software QUINDOS, when evaluating the scanning measurements. The results for a scanning speed of 10 mm/s for profile are shown in Figure 9. As an example, the profile deviations of the external gears on the large ring gear measurement standard are chosen. Figure 10 shows the helix deviations for a scanning speed of 25 mm/s.
In both figures the mean values of the 10 repetitions are shown. The standard deviations are displayed as coloured error bars. The black error bars visualize the expanded measurement uncertainties $U_{95\%} = U(k=2)$ determined by PTB with M3D3 calibration method.

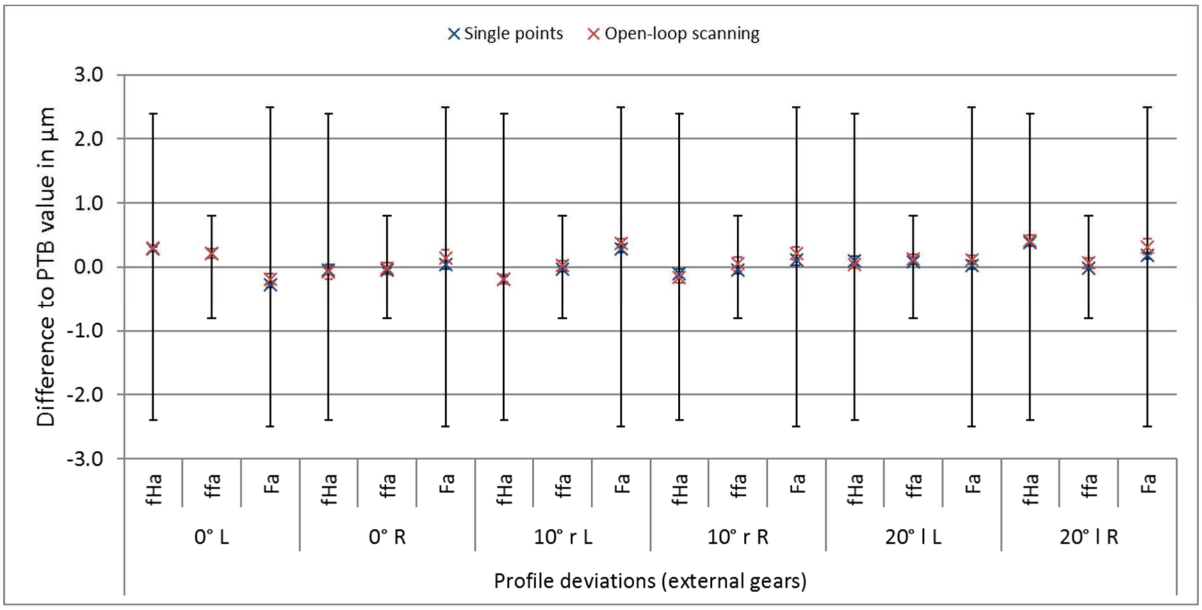

Figure 9: Comparison between tactile scanning and tactile single point probing for profile deviations of external gears

Both figures (Figure 9 and Figure 10) show the same effects. The slope deviations for profile and helix remain nearly constant comparing single point and scanning measurements. There are small deviations less than 0.1 µm between both point acquisition types which are caused by random errors during measurement. The form deviations and the total deviations for profile and helix are for scanning measurements between 0.1 µm and 0.3 µm larger than with single point probing. This is reasonable because the scanning measurements show a higher noise than single point probing. This is mainly caused by environmental influences, such as vibrations, and dynamic effects due to the contact of the ruby probing sphere and the gear surface. By applying the standardized Gaussian filter according to ISO 1328-1 [10] for profile and helix evaluation the noise on the measurement data can be reduced. This leads to nearly the same results between scanning and single point probing. The remaining differences are then dependent on random errors, too.

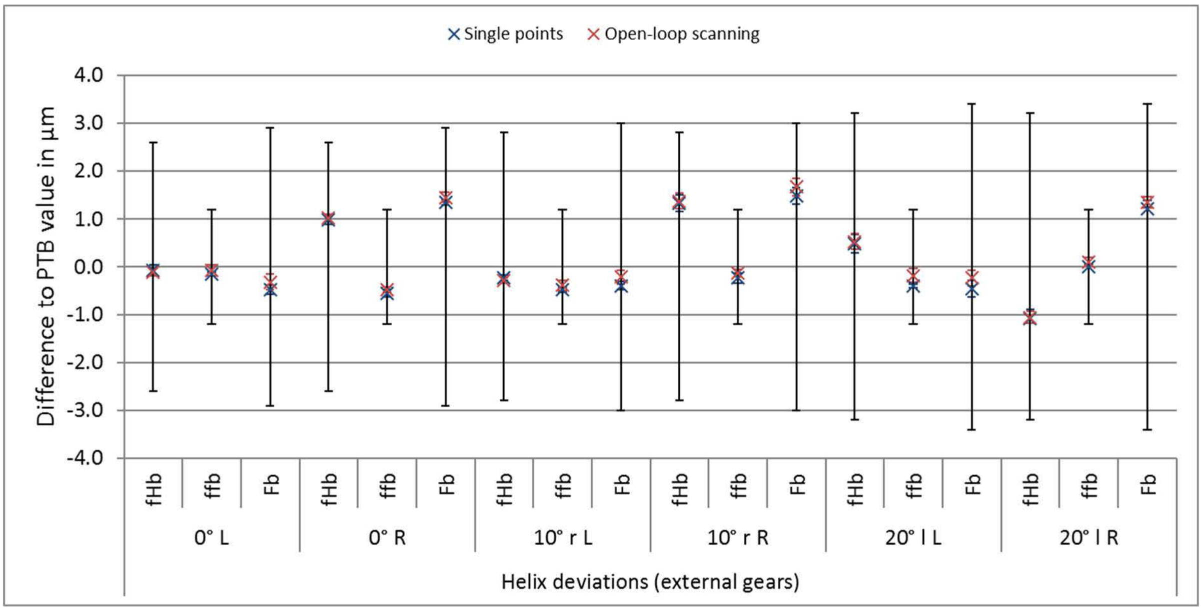

Figure 10: Comparison between tactile scanning and tactile single point probing for helix deviations of external gears

In the next step, optical scanning measurements have been compared to tactile measurements. Therefore, another CMM of type PMM-F equipped with a hydrostatic rotary table was used. The measurement setup is shown in Figure 11.

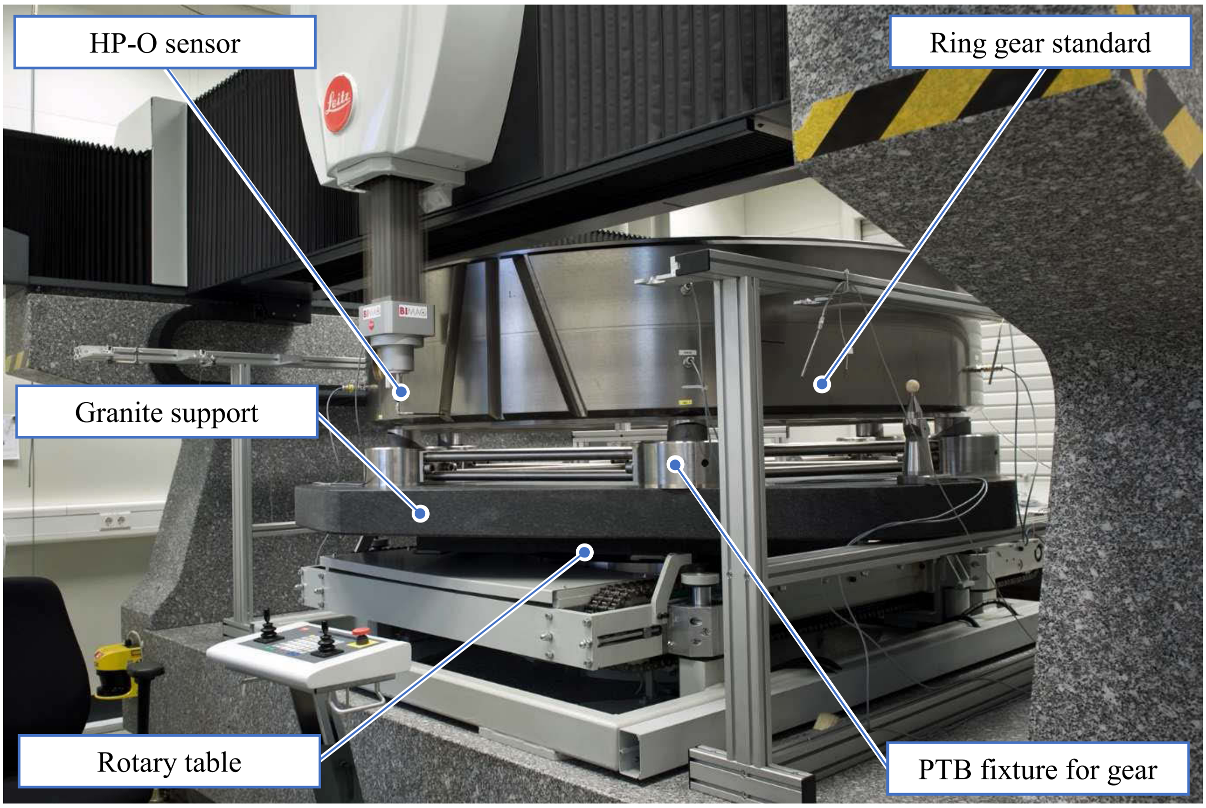

Figure 11: HP-O measurement of the large ring gear measurement standard on a PMM-F with rotary table

The tactile measurements have been executed with a probe diameter of 5.0 mm as defined in the measurement instructions of the large ring gear. A set of 10 repetitions was executed to allow some statistics. The scanning speed for profile was 10 mm/s and for helix 20 mm/s. No filtering was applied in the CMM measurement and evaluation software.

The optical measurements were executed using a stylus with a medium working distance. This means a working distance of 10.5 mm and a working range of ± 1 mm according to focal plane of the sensor. The acceptance angle of the sensor is specified with ± 30°. The exit angle of the laser beam was 0°. Some preliminary tests for choosing an appropriate scanning speed have been done on the external gear with 10° helix angle. These tests have shown an influence of the speed on the form deviations and the total deviations of profile and helix. If the scanning speed is too high, these deviations increase significant. For the comparison to tactile values the scanning speed for profile measurements was set to 15 mm/s and for helix to 30 mm/s. In the controller of the optical probe a pre-filter for measurement data was enabled to remove some outliers, but in the CMM's evaluation software no additional filter was used for a more realistic comparison to the tactile values. In addition, this data was reevaluated with the standard Gaussian filtering according to ISO 1328-1 [10].

The profile evaluation results according to ISO 1328-1 [10] of the external gears are shown in Figure 12. The corresponding evaluations for helix deviations are displayed in Figure 13. In both figures the differences between the mean values of tactile and optical measurements are displayed. The standard deviations of the optical measurements are presented with error bars.

The tactile values cannot be shown with regard to the calibration values since they have not been delivered to PTB in context of the intercomparison yet. This is not of importance because in these two figures the focus lies on the comparison between the tactile and optical measurements performed under same conditions on the same CMM.

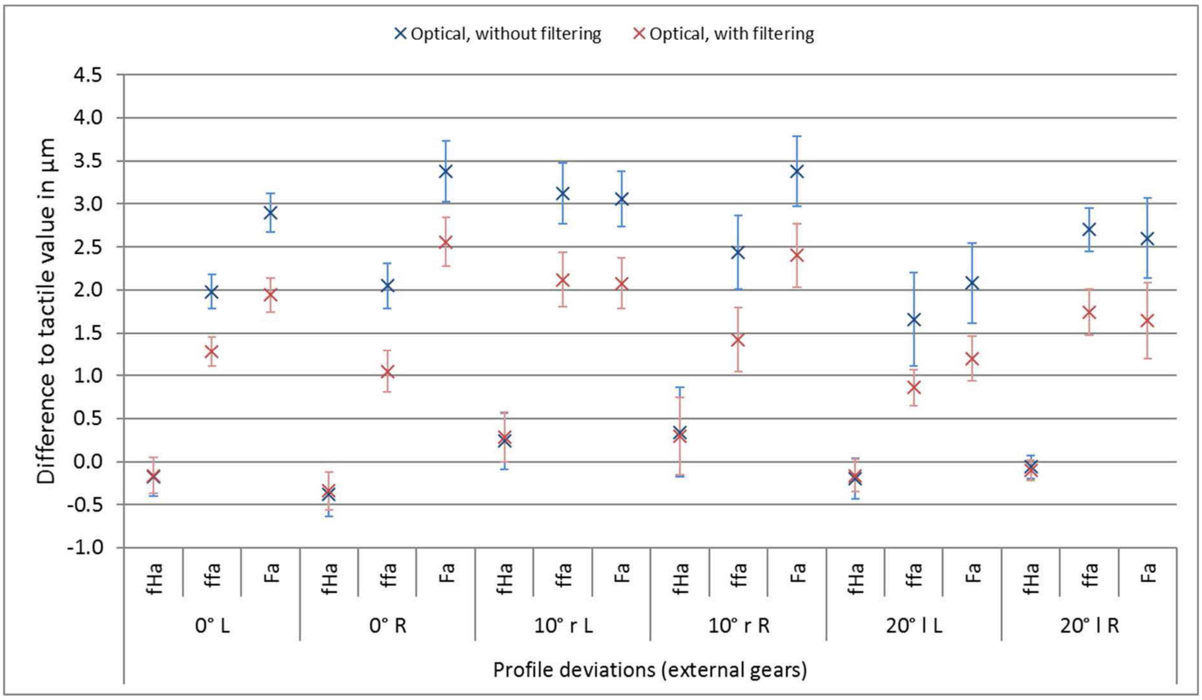

Figure 12: Profile deviations of external gears compared between tactile and optical measurements

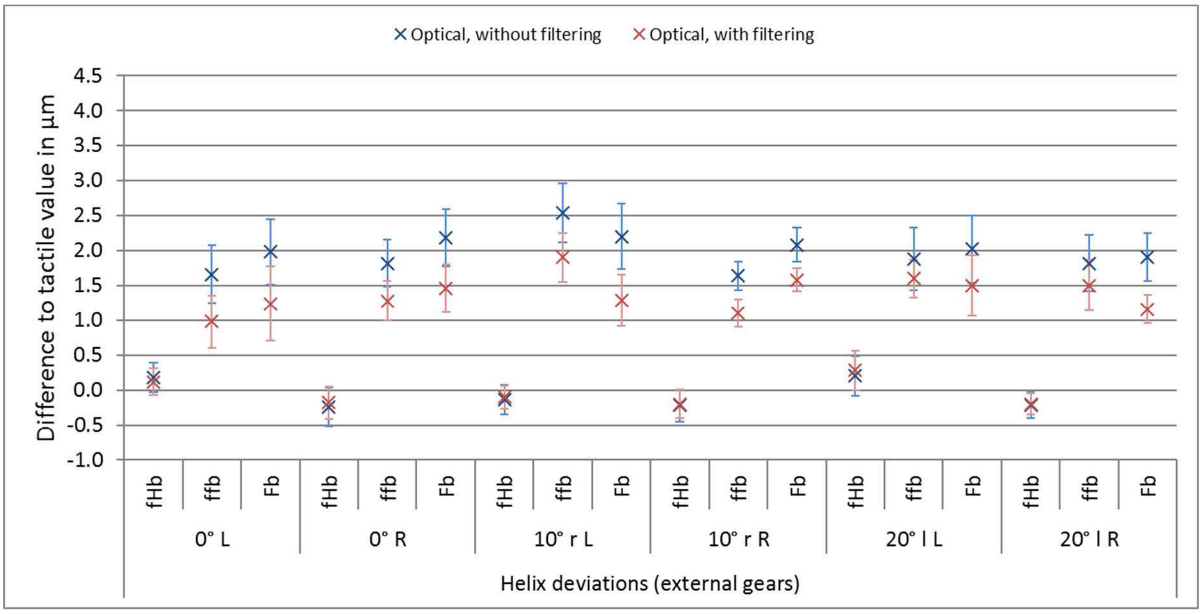

Figure 13: Helix deviations of external gears compared between tactile and optical measurements

It is obvious that the optical values for the profile and helix slope deviations show no significant difference compared to the tactile values. The differences of the mean values are within ±0.5 µm. The standard deviations are about factor 2 larger than for the tactile values and is lower than 0.3 µm for all the evaluated gears.
For the unfiltered form deviations and the total deviations of profile and helix there is not such a good conformity. They all have a systematic offset of 2 µm at minimum and 3.5 µm at maximum and the standard deviations are also higher. They are in the range of 0.4 µm to 0.6 µm and thus about factor 3 to 4 larger. These observations have to be put into context. First it must

be stated that no filtering in the CMM's measurement and evaluation software was applied. Thus, noise and remaining outliers of the optical measurement data have a direct influence for the calculation of form. Second, it has always to be taken into account that the tactile probe applies a mechanical filtering due to its radius when scanning the surface but the optical probe has a spot diameter of 40 µm. This leads to a very small "filtering" due to the integration of reflected light in the spot size. The mechanical surface that is measured by the tactile probe and the physical surface that is measured optically is never the same. Another influence factor especially for large CMM's, that are capable for measuring such a large ring gear measurement standard, is mechanical damping. The tactile probe is in contact with the workpiece during scanning. This leads to a damping of vibrations coming out of the CMM's movement. This is not the case for the optical measurements since they are non-contact measurements.

By filtering the measurement data in the metrology software the offset of the form deviations and the total deviations of profile and helix can be reduced to be more comparable to tactile results. In a first approach a standard Gaussian filter was used. In industrial practice, this filtering of the optical measurement data may be adapted for individual workpiece materials etc.

In summary, these investigations show that the HP-O sensor is of high quality and is well-suited for measuring large gears. One main benefit of the optical measurement method is a reduction of measurement time with regard to area-oriented measurements based on several parallel oriented profiles or helix lines with small lateral distances. If several scan lines are measurement on one flank with optical probes a continuous meander scan can be realized easily, so that approach, search and retract movements for each scan line can be omitted. This leads to a reduction of measurement time about 20 %, if 25 lines are scanned on one flank of the large ring gear measurement standard.

Area-oriented measurements are becoming more important since new manufacturing strategies especially for large gears require more areal related information of flank form. This new measurement strategy enables to analyze the shape of the entire gear flank. Compared to conventional line based evaluations new special modifications can be described and new manufacturing processes can be assessed and corrected [14]. In comparison, this is advantageous especially in the case of existing gear flank modifications as deviations can occur which are not covered by the standard line-oriented measurements.

8. CONCLUSION AND OUTLOOK

A new large ring gear measurement standard developed by PTB and its calibration on a large CMM have been described. The calibration was realized by the M3D3 mobile measuring method developed by PTB, using four tracking laser interferometers. Tactile and optical measurements on this large ring gear measurement standard have been demonstrated.

The optical measurements have shown potential for increasing scanning speed and point density. This allows more information about the geometric flank deviations. Increasing scanning speed means also that more teeth of a gear can be measured in the same time compared to tactile measurements.

These results serve as the basis for installing the first accredited calibration laboratory for large gears at BIMAQ in Bremen on the one hand. On the other hand, these preliminary investigations into large gear measurements are the basis for installing the first large CMM equipped with multi purpose technology in the competence centre WIND at PTB [15].

Both calibration facilities will help to close the existing gap in the traceability chain for large-scaled gear measurements.

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CONTACTS

Dr.-Ing. F. Balzer	felix.balzer@hexagon.com
Dipl.-Ing. N. Steffens, M.B.A.	norbert.steffens@hexagon.com
Dr. rer. nat. Martin Stein	martin.stein@ptb.de
Dr.-Ing. Karin Kniel	karin.kniel@ptb.de