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Experimental uncertainty evaluation by measuring a micro gear standard using focus variation

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Abstract

Micro gears play an increasingly important role in various industrial applications, and the minimization of their deviations is challenging for metrology and manufacturing. A promising method is the focus variation technology, which enables areal measurements of micro gears. Practice-related standards are used to determine measurement uncertainties by comparison with calibration values. In this work, the external micro gear standard of the Physikalisch–Technische Bundesanstalt is used to evaluate experimental measurement uncertainties of a focus variation coordinate measurement system for the first time. The traceable standard with modules between 0.1 and 1 mm is calibrated using micro tactile coordinate measurements. Optical and tactile measurements are then compared. As a result, small expanded measurement uncertainties of less than 4 µm are achieved.

Keywords: measurement uncertainty, focus variation, micro gear measurement standard, gear metrology, micro coordinate metrology

1. Introduction

Micromechanical systems are gaining increasing importance in industrial applications due to a trend toward miniaturizing electromechanical components. Micro gears are an integral component of micro gearboxes, single gear pairs, and one-stage planetary gear sets, which function as kinematic transmission of forces and torques [1]. Micro gears are used across all industries, as they are indispensable in precision mechanics, medical engineering, and robotics [2]. Härtig *et al* define micro gears in terms of a module range of 1 µm to 1 mm [3]. Due to technological limits within manufacturing processes concerning structural dimensions, micro gears exhibit relatively large manufacturing deviations compared to macro gears. Because of small component sizes and complex three-dimensional geometries, manufacturing micro gears with high-quality requirements is a significant challenge for manufacturers [4]. Quality assurance is, therefore, of great relevance. In the case of micro components, such as gears of a module $<$ 1 mm, measurements with a very low uncertainty are required. To this end, metrology manufacturers have already implemented extensive developments with great technological effort [5]. Nevertheless, task-specific measurement uncertainties for micro gears with currently available measuring equipment are still close to the size of their features to be measured [6]. Fast optical measurements could be suitable for 100% inline measurements of micro gears near the production process on the shopfloor [7].

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This paper uses optical measurements based on focus variation metrology to evaluate measurement uncertainties of gear deviation parameters using the external micro gear standard of the Physikalisch–Technische Bundesanstalt (PTB) for the first time. After introducing the current state-of-the-art in focus variation metrology, an approach to experimentally evaluate measurement uncertainties is described, and the experimental setup is explained. Subsequently, uncertainty results are presented, which underline the future potential of optical micro gear metrology.

2. State-of-the-art

Measuring methods for quality assurance of micro gears can be divided into tactile, optical, tactile-optical, and computed tomographic measuring methods. Tactile measurements are performed using micro-coordinate or gear-measuring machines [8]. Scanning is used with specific micro-probes, which are available with diameters starting at about 20 µm [9]. Optical measurements are carried out using various 2D or 3D methods, such as autofocus or chromatic confocal sensor technology [10]. Tactile measuring methods have lower measurement uncertainties, while optical or computed tomographic methods allow higher information densities [11].

Due to relatively short measurement times, inline optical metrology implemented near the manufacturing process is suitable for the quality assurance of micro gears. Focus variation technology is up-and-coming for such applications [12]. The critical component of this system is a precision optical system that contains multiple lens systems. It can be equipped with different magnification levels to measure objects of various sizes in variable resolutions. Modulated white light is directed into the optical path of the measurement system using a semi-transparent mirror and is focused onto an investigated component. When light reaches the topography, it is reflected in different directions. Reflected light rays hitting the lens are focused using optics and reach a light-sensitive sensor. Because of the shallow depth of field of the lens, only small topography areas are ever in focus [13]. It is necessary to move the sensor unit vertically along the optical axis so that the scope of focus varies over the sample topography to enable depth measurements.

Depth evaluation is performed according to the following scheme. First, a measure of sharpness is calculated for each object point detected by the sensor. Then, focus positions are analyzed to estimate the Z-position of the object [10]. Contemporary systems consist of high-precision air-bearing axes with linear motors and thermally stable scales made of Zerodur. State-of-the-art µCMMs are also equipped with a fully automatic rotation and tilt unit to inspect rotationally symmetrical components. The vertical resolution represents the smallest resolvable height level of a surface. It depends on the lens and can be up to 3 nm [10].

Regarding comparable measurement methods, Neuschaefer-Rube *et al* investigated focus variation technology with micro gears [11]. Tactile systems have limited suitability for micro examinations, and the evaluation of micro gears is only possible with unique tactile designs. Their investigation inspected a gear tactilely and optically using focus variation technology. Between both methods, the deviations ranged within 2.5 µm [11]. Newton *et al* examined the suitability of focus variation for measuring additive metal surfaces [14]. Jantzen *et al* already investigated focus variation technology to measure the PTB external micro gear measurement standard [15]. The advantages of focus variation technology are fast and contactless areal measurements. In contrast, unwanted artifacts, increased uncertainties, and a significant impact of impurities on the results were disadvantages of the focus variation technology [15].

In former investigations of Gauder *et al* [7], a Design of Experiments was conducted, and experimental measurement uncertainties were evaluated following the Guide to the Expression of Uncertainty in Measurement (GUM) [13, 16]. The aim was to optimize the tradeoff between measurement uncertainty and measurement time using focus variation technology. This optimization method used a meta-model and hyperparameter tuning to allow the adjustment to specific operating conditions and use cases. This research provided a more detailed insight into how the focus variation technology works. It was shown that this optical method is suitable for measuring micro gears and has a potential for optimization in an area of research that has been fragmentarily studied. With the help of these investigations, it was also possible to transfer optimum parameters to novel and advanced focus variation systems [7]. In addition, this approach also enabled the transfer from mechanical single flank rolling tests to simulative variants based on focus variation with comparably low measurement uncertainties. Prior research struggled to achieve low micro gear measurement uncertainties with focus variation, critical due to the very low tolerances in the micro gear domain. This paper highlights the latest potential of this technology, especially for single flank rolling tests derived from these optical measurements, a topic previously unaddressed in micro gears [17–19].

Goch *et al* deal with two-dimensional gear evaluations, which can utilize the point clouds of optical measurements. Thus, no reduction of the optical measurement data is necessary. According to Goch *et al*, evaluating areal gear measurements will be essential to future investigations. Therefore, within the scope of their publication, an areal approach for gear evaluations is described. However, this concept is limited to the characterization of surfaces and thus does not include the derivation of parameter-based gear deviations. This deficit is currently a significant barrier to optical measurement data [20].

Overall, it can be stated that, at present, no optical micro gear measurements through focus variation coordinate measuring technology have been carried out on a national standard. Moreover, no experimental measurement uncertainty investigation has been realized in the meantime. Previous research has shown this measurement technique's potential, but there is a lack of specific uncertainty results, which are essential for micro gear quality assurance.

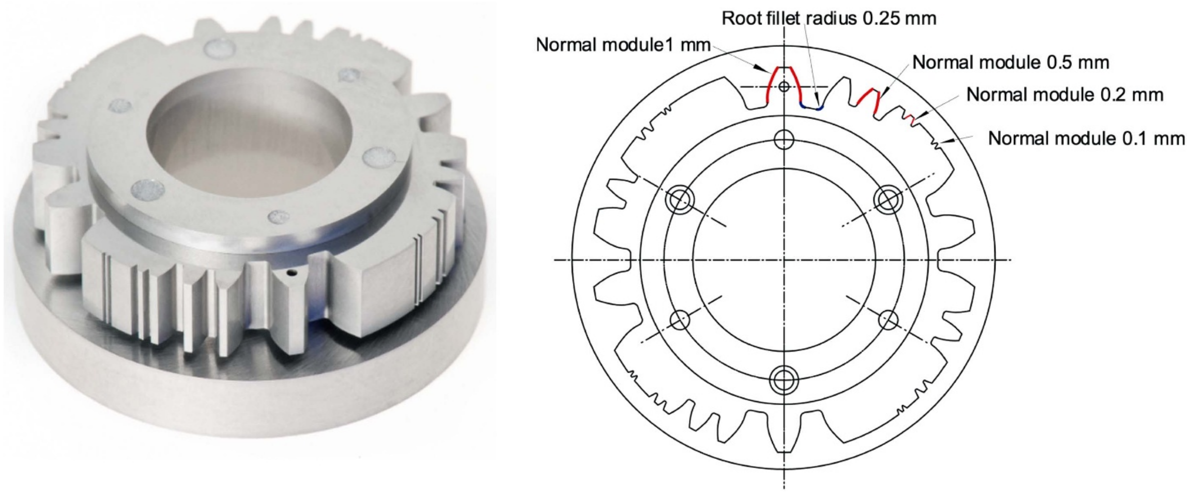

Figure 1. External micro gear measurement standard.

3. Experimental setup

This chapter describes the experimental setup of this task-specific uncertainty evaluation approach. ISO 15530-3 is the basis for the determination since the uncertainty is evaluated based on the external micro gear measurement standard as a calibrated workpiece [21].

3.1. External micro gear measurement standard

The external micro gear measurement standard (see figure 1) was developed in 2014 within the scope of a national research project [6]. It consists of three parts: the gear and two disks serving as reference bands, joined by pinning and gluing to ensure long-term stability. The gear part is manufactured using wire electric discharge machining.

This part embodies four different involute gear geometries with normal modules ranging from 1 mm to 0.1 mm (see table 1). Its smallest module has not been calibrated, since precision spheres for tactile probing are unavailable with diameters below 125 µm. However, the gear flanks marked in figure 1 with modules 0.2 mm, 0.5 mm, and 1 mm can be calibrated on micro coordinate measuring machines with tactile sensors, providing reference values with low measurement uncertainties. For more information on previous comparison measurements on this part, the reader is referred to [15].

3.2. Tactile calibration process

The Zeiss F25 tactile CMM was used for calibration and a reference to compare with optical measurements derived from focus variation technology. With a maximum permissible error for a nominal length L of $E_0 = \left(0.25 + \frac{L}{666}\right)$ µm, this system delivers high precision measurement points [22]. The micro gear standard was initially adjusted to a maximum runout error of <20 µm using an adjustment element placed on a zero-point clamping system to prevent shaft probing (see figure 2). This alignment does not influence the workpiece coordinate system used.

Table 1. Properties of the external micro gear measurement standard.

Parameter	Value
Normal module m_n	0.1 mm/0.2 mm/0.5 mm/1 mm
Number of teeth (theoretical) z	198/99/38/18
Pressure angle α	20°
Helix angle β	0°
Profile shift coefficient x	0 [-]
Tip diameter d_α	20 mm
Face width b	4 mm
Material	Carbide (CF-H40S)
Coefficient of thermal expansion (CTE)	$5.4 \cdot 10^{-6}$ K^{-1}

Single-point probing was used to achieve comparability with optically recorded measurements, where the probing of the individual measurement points is decoupled. For a maximum point density, 99 profile lines with 206 points each were measured over one flank, corresponding to the technical maximum of the CMM. Consequently, the calculation of classical gear deviations based on identical measurement points between both techniques ensures comparability with various measurement principles. Table 2 shows the essential tactile calibration parameters. Because of the minimum probing sphere diameter of 125 µm, the tactile probing system cannot measure the smallest module of $m = 0.1$ mm. Therefore, modules of 0.2 mm, 0.5 mm and 1.0 mm have been examined.

The workpiece coordinate system setup for tactile calibration measurements is described in the following section, identical to the procedure successfully applied by Jantzen *et al* [1]. In this case, the front surface corresponds to the top site of the gear standard. First, the front surface of the standard was registered by 12 points to determine $z = 0$ accurately. Next, the outer cylinder of the standard was registered using three individual circles, from which a cylinder was calculated as a geometric substitute element by using 500 measurement points. The symmetry axis of the cylinder

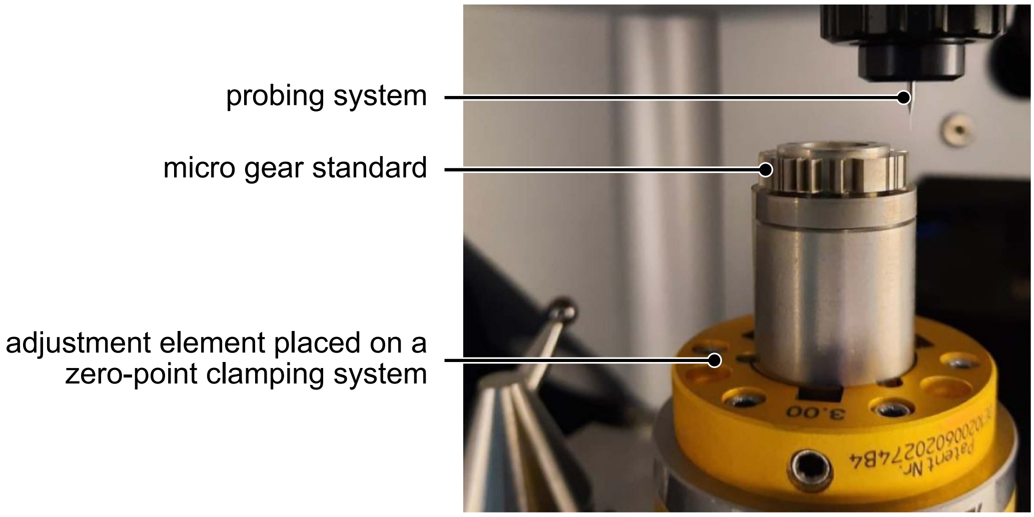

Figure 2. Tactile probing setup using a Zeiss F25.

Table 2. Tactile measurement parameters.

Parameter	Value
Probe sphere diameter	125 µm
Probe shaft length	2 mm
Probe material	Ruby
Probe shaft direction	$-z$
Probing force	1 mN
Measurement strategy	Single point probing
Number of profile lines	99
Number of points per line	206
Filter cut-off wavelength (profile)	67 µm
Filter cut-off wavelength (helix)	17,5 µm ($m_n = 0.2$ mm) 40 µm ($m_n = 0.5$ mm) 80 µm ($m_n = 1.0$ mm)
Start of evaluation (profile)	19,6 µm ($m_n = 0.2$ mm) 19 µm ($m_n = 0.5$ mm) 18 µm ($m_n = 1.0$ mm)
Measured face width (helix)	2 mm
Average duration	∼12.5 h
Feed between probing	10 mm s^{-1}
Filter	None
Temperature range	$(20 \pm 0.5°)$ Celsius

determined $x = 0$ and $y = 0$. Finally, the orientation of the x-axis was determined by registering a circle in the drill hole on the reference tooth with module $m = 1$ mm (see figure 1). After the acquisition, the measurement data was evaluated using line-based profile and helix deviations [23]. The tactile reference measurements on the Zeiss F25 are used to calibrate the gear standard, aligning with the calibration requirements of ISO 15530-3. Additionally, our collaboration with the National Metrology Institute of Germany ensures that our calibration process meets the necessary traceability standards. By using the tactile measurements as a calibrated reference, this approach can estimate task-specific measurement uncertainties for the optical measurements in accordance with ISO 15530-3.

3.3. Optical measurement process

Further development of focus variation technology raises the question, of which uncertainties are achievable in optical measurements of gears with a module $m \leqslant 1$ mm. For this purpose, the micro gear measurement standard was examined on a state-of-the-art Bruker Alicona µCMM after the tactile calibration. The standard was therefore clamped in a three-jaw chuck. Irrespective of the orientation in the machine coordinate system, the point cloud is orientated using a common iterative closest point algorithm for evaluation according to gear deviations. In contrast to the tactile coordinate system, the gear coordinate system does not influence the measurement process. Because of the contact-free optical measurement, no specific orientation between the machine coordinate system and the gear coordinate system is therefore needed. The layout and axes of the focus variation system are presented in figure 3. Here, the optical axis along the Z-axis for depth evaluation, the rotational axis R for 360° measurements, and the tilt axis T to minimize reflections are visualized. A detailed description of the measurement setup is shown in figure 4.

This measurement strategy aimed to minimize reflections from metallic surfaces of the standard and investigate the accuracy limits of focus variation technology. The Alicona 'Real3D' measurement strategy enables combined measurements at different rotation angles. This technology transforms the individual measurements into the coordinate measurement system based on positional and grayscale information of each measuring point. Consequently, a fused 360° data set is created from overlapping measurements [24]. Using an integrated polarizer, a moderate tilt angle T of $+15°$ (see figure 3), an increased internal outlier filter of 0.9 [-] based on measurement point repeatability, an individual measurement overlap percentage of 85% for the incremental measurements to enable full 360° measurements, and a complete measurement width in terms of the X-dimension (see figure 3) were helpful for this achievement. Otherwise, local gaps within the

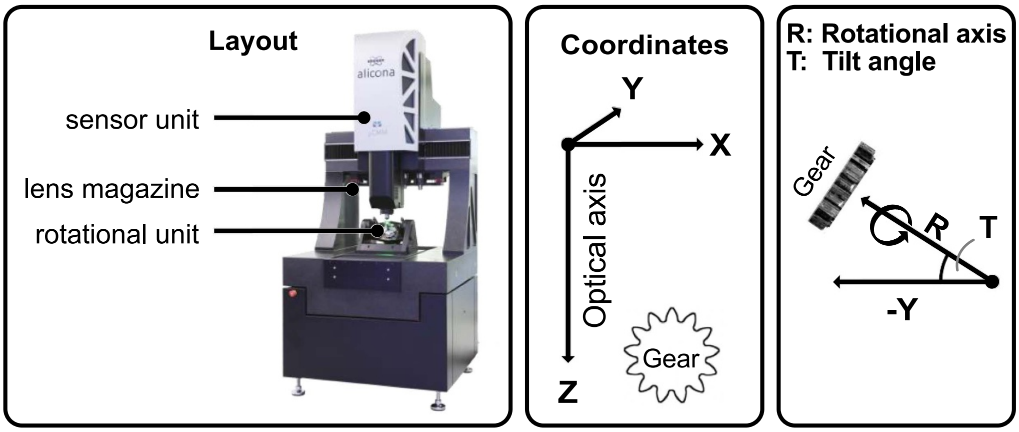

Figure 3. Layout and axes of the focus variation system (Image source: Alicona Imaging GmbH).

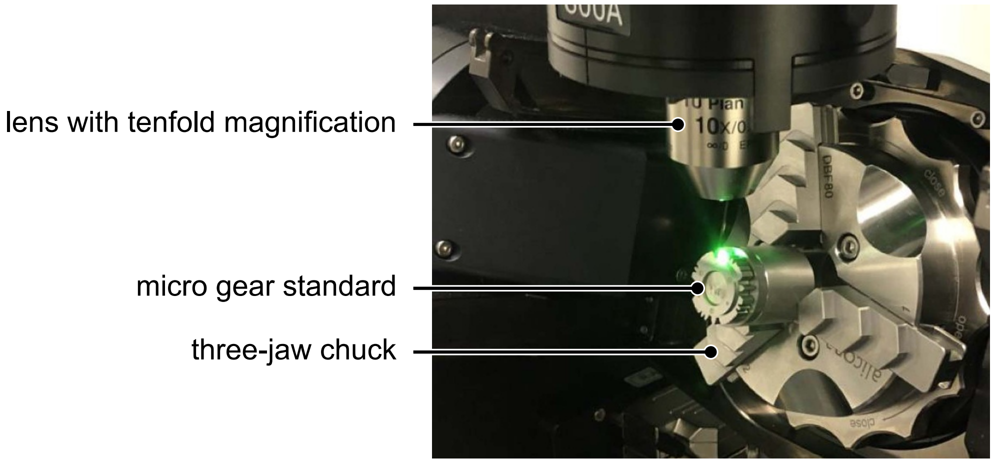

Figure 4. Optical measurement setup using focus variation technology.

point cloud prevent a measurement evaluation. Tenfold lens magnification was chosen to ensure a high optical resolution for the extensive dimensions of the standard. A down-sampling factor of 4 used for the point reduction was selected for the same purpose: to realize a high number of measuring points while capturing the whole dimension of the standard. The duration per uncertainty-reduced reference measurement for all teeth of the standard was approximately 17.3 h, with an average number of about 2.85 million points. An overview of the used parameters can be found in table 3. After optical measurement, points are extracted along the nominal tactile lines within a window of ± 50 µm. The selected interval maintains the integrity of the down-sampled optical measurement points by only selecting the closest optical neighbors of the tactile reference points, facilitating accurate comparisons.

Table 3. Bruker Alicona µCMM measurement parameters.

Parameter	Value
Measurement strategy	Alicona 'Real3D'
Magnification	10x
Tilt angle	$+ 15°$
Exposure time	3.0 ms
Contrast	0.5 [-]
Vertical resolution	0.1 µm
Lateral resolution	6.1 µm
Downsampling	4x
Number of points	~2.85 Mio.
Width of measurement	13.2 mm
Polarization	Active
Precision mode	On
Measurement overlap percentage	85%
Outlier filter	0.9
Average duration	~17.3 h
Temperature range	$(20° \pm 0.5°)$ Celsius

4. Optical measurement data

An optimized optical measurement program was developed to achieve low measurement uncertainties while maintaining a sufficient point density regardless of the measurement time. The complete external micro gear measuring standard can be measured within one program. One of the 20 optical measurement data sets to be investigated is shown in figure 5.

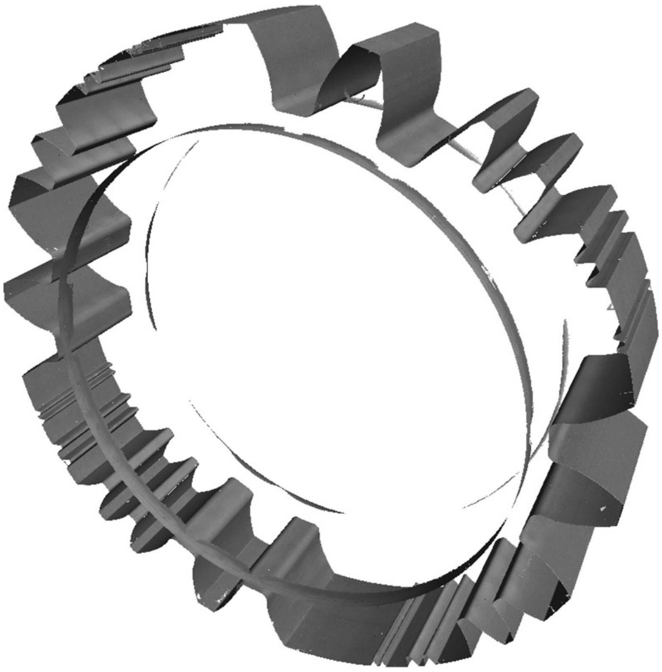

Figure 5. Measured point cloud of the gear standard.

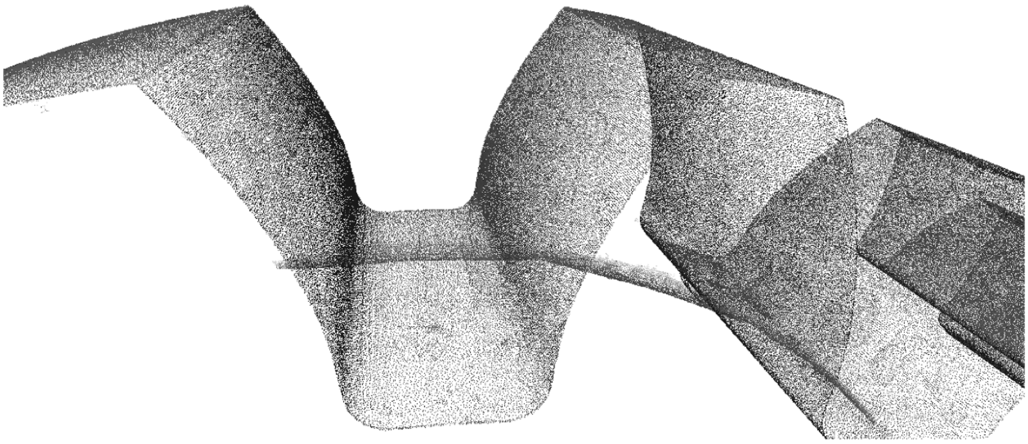

Figure 6. Visualization of optical measurement data on a point basis.

In figure 5, areas have been generated from the actual measurement points for improved visibility. Individual measurement points are shown in figure 6 to understand the point densities of the 20 data sets. The point density behaves consistently over different modules and tip and root areas because of the fixed pixel distances of the image sensor.

A measurement time of approximately 17.3 h for a complete measurement appears large at first glance. Still, it is relativized compared to the tactile method, which requires 12.5 h for only four teeth of the gear standard. Furthermore, the teeth' complete flank widths were measured, not only a section of 2 mm in the helix direction, which must be considered in tactile measurements to prevent premature shaft contact. In addition, the smallest module $m = 0.1$ mm, which cannot be measured with a minor probing sphere diameter of 125 µm, was also optically detected.

5. Measurement uncertainty evaluation

5.1. Uncertainty model

As no calibration certificate is available for the micro gear measurement standard, tactile calibrations were performed to serve as a reference. To evaluate optical measurement uncertainties when measuring the national gear standard, ISO 15530-3, as well as the GUM, were used as guidelines [16, 21]. Therefore, 20 repeat measurements were chosen [21]. In the first step, 20 tactile measurements were performed to evaluate calibration uncertainties when measuring the micro gear measurement standard. The gear standard was measured 20 times using focus variation in the second step. With the calibration uncertainty evaluated in the first stage, expanded uncertainties of focus variation measurements are assessed by comparing gear deviations of optically and tactilely measured point clouds. Equation (1) describes the expanded measurement uncertainty,

$$U_k = k \cdot \sqrt{u^2_{\text{cal,p,tactile}} + u^2_{\text{cal,bias,tactile}} + u^2_{\text{p,optical}} + u^2_{\text{bias,optical}}}. \tag{1}$$

Here, $u_{\text{cal,p,tactile}}$ represents the standard deviation of gear deviation parameters within tactile repeat measurements. The contribution $u_{\text{cal,bias,tactile}}$ stands for tactilely evaluated gear deviations. $u_{\text{p,optical}}$ equals the standard deviation within optically estimated gear deviations, $u_{\text{bias,optical}}$ describes the difference between optically and tactile evaluated mean gear deviations, and k expresses the coverage factor, which is set to two for a confidence interval of approximately 95.5%. The respective contributions result in different coefficients, leading to a unique composition of expanded measurement uncertainties U_k.

In the first stage, the expanded calibration uncertainty of the tactile repeat measurements is determined. Due to the measurement of the standard and the assumption of the repeat measurements as a calibration measurement, the contribution of the calibration uncertainty is set to zero. The standard deviation within the tactile repeat measurements is represented through $u_{\text{cal,p,tactile}}$. The coefficient $u_{\text{cal,bias,tactile}}$ describes the deviation between the mean value within the tactile repeat measurements and a reference value set to zero, because of the use of an ideal gear standard. The standard deviation within the optical repeat measurements is represented through $u_{\text{p,optical}}$. The coefficient $u_{\text{bias,optical}}$ describes the deviation between the mean value within the optical repeat measurements and the value of one gear deviation from one tactile reference measurement.

Contributions resulting from variations in materials and production are neglected after estimation because of the carbide properties and use of the national gear standard following ISO 15530-3 [21]. When comparing different measuring systems with a calibrated workpiece, the task-specific measurement uncertainty is determined only for a single workpiece, not a series of parts from a production process. In that case, the influences of the production processes are omitted, and only the effects of the current workpiece are considered. The maximum expansion of the standard was additionally considered by estimating the possible variation of the expansion coefficient due to the scattering of the material properties. The outer diameter of 20 mm, the CTE uncertainty of the carbide of $5.7 \cdot 10^{-9}$ K^{-1}, the variation of the temperature in the measuring room of ±0.5 K, and a rectangular uncertainty distribution resulted in an expanded uncertainty of 0.13 nm ($k = 2$). Therefore, the uncertainty of the thermal expansion is negligible when uncertainties in the micrometer range are considered.

In the first step, the tactile calibration contributions $u_{\text{cal,p,tactile}}$ and $u_{\text{cal,bias,tactile}}$ are determined. The second step compares the optical results with the tactile calibrations with the help of $u_{\text{p,optical}}$ and $u_{\text{bias,optical}}$. This approach allows tasks-specific experimental uncertainty assessments of focus variation measurements compared to precise tactile calibration measurements based on gear deviation parameters according to ISO 15530-3 [21].

Table 4. Tactile calibration uncertainties of 20 repeat measurements in µm.

Parameter	$u_{\text{cal,p,tactile}}$	$u_{\text{cal,bias,tactile}}$
Total profile deviation F_α	0.1	0.4
Profile slope deviation $f_{H\alpha}$	0.1	0.2
Profile form deviation $f_{f\alpha}$	0.1	0.3
Total helix deviation F_β	0.1	0.4
Helix slope deviation $f_{H\beta}$	0.1	0.3
Helix form deviation $f_{f\beta}$	0.0	0.3

5.2. Tactile calibration uncertainties

The evaluated tactile calibration uncertainties are shown in table 4. Due to the non-existence of a standard for areal evaluation of gear deviations, a line-based approach according to ISO 1328-1 was used to evaluate comparable gear deviation parameters [23]. The reason for only regarding the module 0.2 mm comes from preliminary investigations on this gear standard by the PTB. Here, the evaluated calibration uncertainties of the standard were identical for all three modules. Therefore, this assumption was made to save 500 h of additional measurement time [15].

5.3. Task-specific optical measurement uncertainties

Table 5 shows both optical uncertainty contributions described in equation (1). Individual uncertainties were obtained by averaging over all flanks. The optical point cloud is initially aligned based on characteristic features (front surface, tip area, root area), and the relevant flank areas are extracted. This procedure is followed by a standardized evaluation of the gear deviations according to ISO 1328-1 [23].

5.4. Resulting measurement uncertainties

The expanded uncertainties calculated using equation (1) are presented in table 6.

6. Discussion and conclusion

The evaluated calibration uncertainties for the repeat measurements of the external micro gear measurement standard behave similarly to previous investigations [15]. These proved that tactile calibration uncertainties acted independently of measured modules. Under the same assumption, expanded uncertainties for other modules were evaluated. For an analysis of individual uncertainty contributions, results are shown in figure 7 regarding $m = 0.2$ mm. This behavior indicates that the most significant contribution is $u_{\text{bias,optical}}$, representing a systematic deviation between both measurement methods. The standard uncertainties within optical measurements are comparatively low and, on average, slightly higher than the resulting uncertainties of the tactile calibration itself.

Table 5. Optical measurement uncertainties of 20 repeat measurements in µm.

Parameter	$u_{\mathrm{p,optical}}$ $m = 0.2$	$u_{\mathrm{p,optical}}$ $m = 0.5$	$u_{\mathrm{p,optical}}$ $m = 1.0$	$u_{\mathrm{bias,optical}}$ $m = 0.2$	$u_{\mathrm{bias,optical}}$ $m = 0.5$	$u_{\mathrm{bias,optical}}$ $m = 1.0$
F_α	0.3	0.3	0.3	0.8	0.6	1.0
$f_{H\alpha}$	0.5	0.3	0.4	0.4	0.9	1.8
$f_{f\alpha}$	0.4	0.2	0.2	0.8	0.8	0.9
F_β	0.5	0.6	0.5	1.5	0.9	0.8
$f_{H\beta}$	0.8	0.5	0.5	1.6	0.9	0.8
$f_{f\beta}$	0.3	0.5	0.5	1.3	0.8	0.8

Table 6. Expanded measurement uncertainties ($k = 2$) in µm for different gear modules.

Parameter	$U_{m=0.2}$	$U_{m=0.5}$	$U_{m=1.0}$
F_α	1.9	1.6	2.2
$f_{H\alpha}$	1.5	2.0	3.7
$f_{f\alpha}$	1.8	1.7	1.9
F_β	3.2	2.3	2.2
$f_{H\beta}$	3.5	2.2	1.9
$f_{f\beta}$	2.7	1.9	2.0

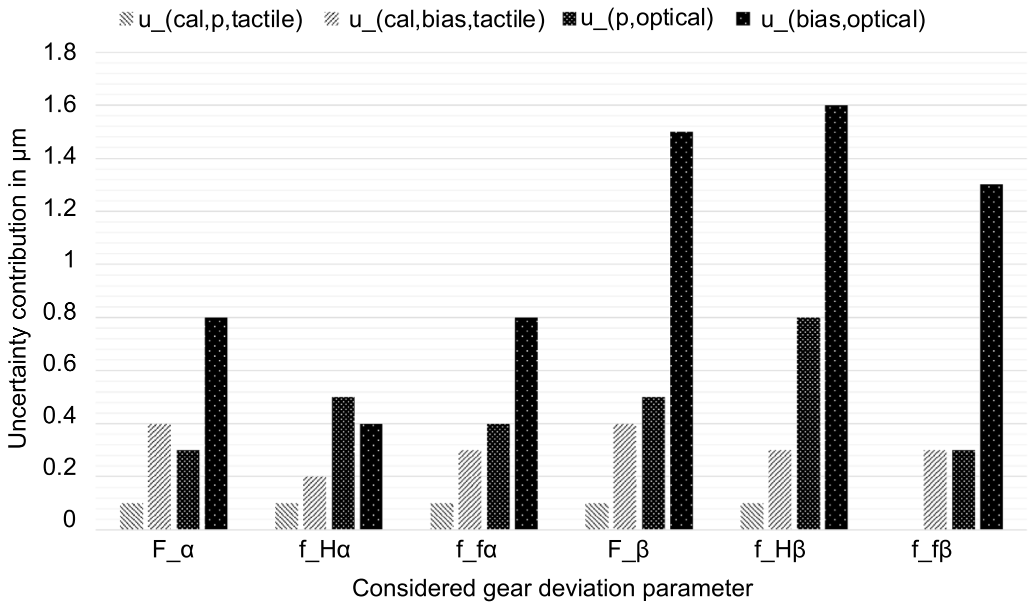

Figure 7. Measurement uncertainty contributions ($k = 1$) for $m = 0.2$ mm.

In the following consideration, a distinction is made between variations of optical detection and a systematic variation due to linear motion and data processing. In terms of the standard deviation within optically evaluated gear deviations $u_{\mathrm{p,optical}}$, the deviations in profile and helix direction behaved similarly. Since no magnification level can capture the complete face width of the external micro gear measurement standard, the sensor must be shifted along the Y-axis (see figure 3) to calculate measurement points into a uniform point cloud. Consequently, the sensor captures the standard surface at different positions along the axis. However, uncertainties can increase due to a systematic deviation caused by axis movement along the rotation axis and a subsequent data fusion.

Furthermore, the optical measuring system's vertical resolution (mainly relevant for profile deviations) is significantly larger than the lateral resolution (primarily appropriate for helix deviations). While the vertical resolution represents the smallest resolvable height level, the lateral resolution describes the smallest resolvable characteristic measured by the image sensor. However, the vertical resolution is limited by the optical accuracy of a lens (here 0.10 µm). In contrast, the lateral resolution is given by the pixel distances of an image sensor and its specific lens (approx. 0.76 µm). Consequently, the lateral resolution is lower than the vertical resolution and can influence increased uncertainties of helix deviations.

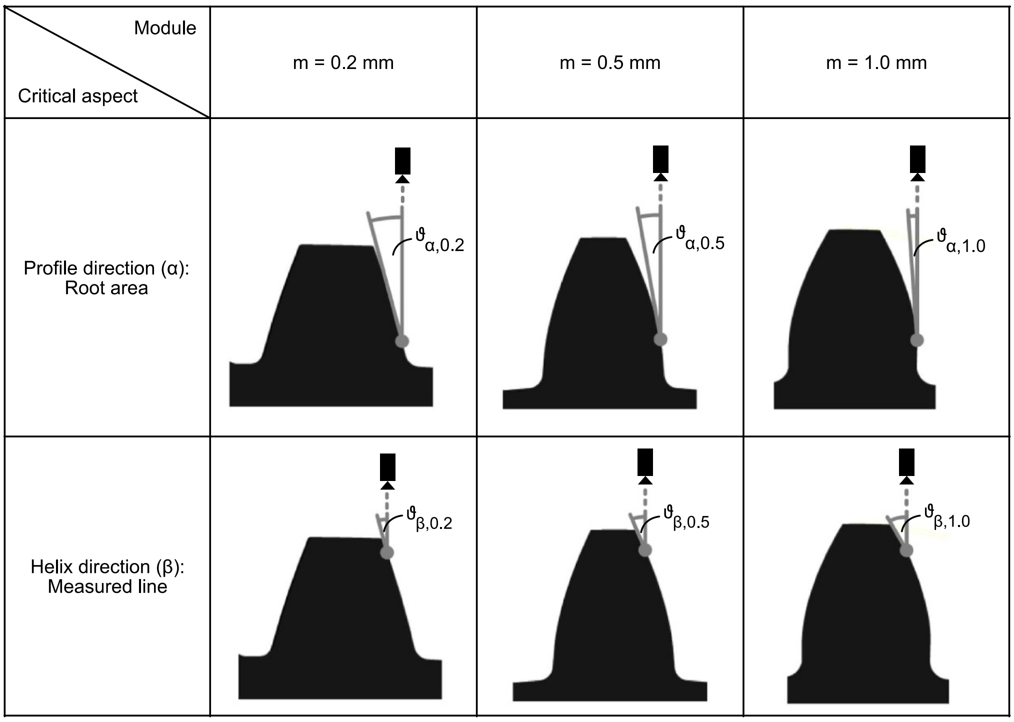

Figure 8. Influence of the measurement vertex angle on the optical measurability of one gear flank.

A contour analysis of the three module geometries shows a slight tendency for uncertainties to decrease in helix direction and increase in profile direction as the module increases. We, therefore, introduce the term 'measurement vertex angle' to represent the angle ϑ between the measurement instrument's optical axis and the gear flank's profile surface. A low measurement vertex angle describes a steep angle between the standard's profile topography and the axis of the optical sensor (see figure 8). This results in a worsened optical measurability. In contrast, large vertex angles are helpful since the gear's profile topography is almost parallel to the image sensor and can be detected with a larger sensor area. In addition, no manifestation into depth levels occurs.

Regarding profile geometry, teeth of module $m = 0.2$ mm have an approximate straight contour. With an increased module, this contour is changed into a more curved contour, as described in figure 9. This relationship influences the vertex angle. Furthermore, the root area bends, and the tip area flattens with an increasing module. Consequently, uncertainties of the profile deviation tend to increase since a low measurement vertex angle in the root area worsens optical point detection due to the steepness of the topography.

In contrast, this trend tends to behave the other way for helix deviations. For the evaluation, the measured helix line is in the flattening upper area of the contours. The measurement vertex angle also increases here due to the increased flattening in these regions within higher modules (see figure 8). An observed measurement vertex angle change between different modules tends to decrease the measurement uncertainty. This observation might be a possible explanation for the uncertainty trends identified. However, future studies must consider a valid basis for these effects.

To underline this hypothesis, an additional way of explaining the effect of the measurement vertex angle in case of the focus variation measurement is shown in figure 10. Based on the optical measurement data, the actual individual point repeatabilities have been calculated. The point-based results ultimately show the same trends as the derived gear deviation parameters.

Despite maximum measurement parameters regarding low uncertainty, some influences could not be further minimized. First, individual outliers should be mentioned here. While using optimized filtering, a small number of outliers (approx. 10 per point cloud with about 2.85 million points) is still present and can influence gear deviations. Furthermore, reflections on metallic surfaces reduce contrast for optical detection despite polarization, optimized exposure, and tilting. To fully demonstrate the impact of the measurement vertex angle, it would be beneficial to conduct additional helix measurements of the involute. This approach would help assess how the vertex angle influences measurement uncertainty, provided that the necessary data are available. Our optical measurements showed decreased systematic deviations compared to previous studies [15]. This improvement is indicated in reduced deviations between tactile and optical measurements. In addition, our results should be interpreted as comparative differences from tactile reference measurements rather than absolute uncertainties. This acknowledges the current limitations in traceability to national standards. Our work aims to provide a foundation for future research focused on achieving full

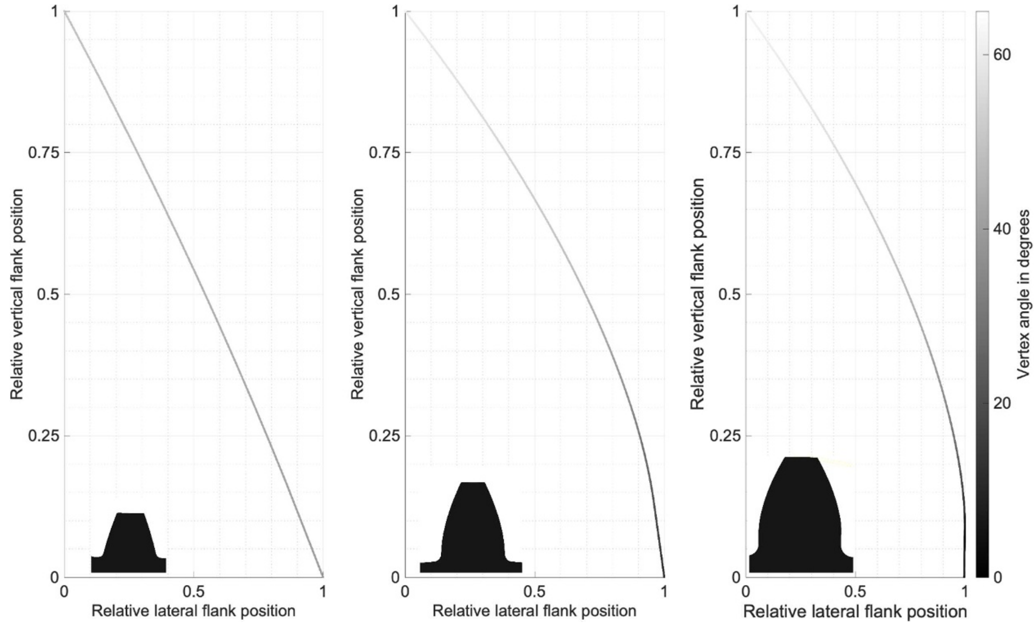

Figure 9. Relative flank contours for $m = 0.2$ mm (left), $m = 0.5$ mm (middle) and $m = 1.0$ mm (right) with the resulting vertex angle ϑ to the optical sensor axis.

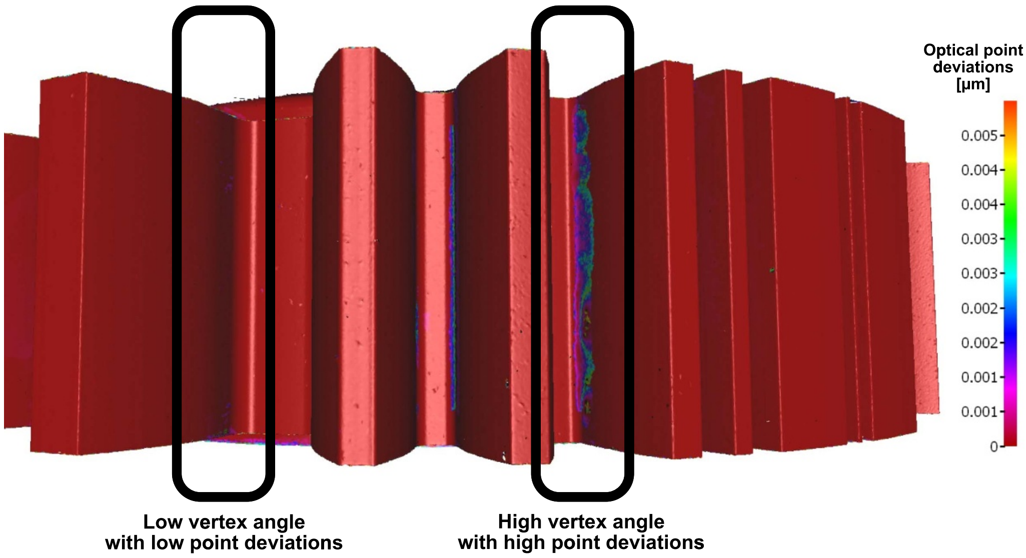

Figure 10. Optical point deviations revealing the effect of the measurement vertex angle.

traceability and comprehensive uncertainty budgets. In conclusion, the absence of a standard for the areal evaluation of gear deviations should also be addressed in future investigations to take advantage of areal measurement methods. Beyond areal methods, we propose simulating single flank rolling tests based on areal data to predict functional characteristics, leveraging the data's full potential. Future work should also aim to extend the utility of focus variation measurements in practical gear metrology applications, based on the capabilities of this technology demonstrated in this uncertainty estimation approach.

Data availability statement

The data cannot be made publicly available upon publication due to legal restrictions preventing unrestricted public distribution. The data that support the findings of this study are available upon reasonable request from the authors.

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