AREAL CHARACTERIZATION OF MICRO GEARS BY MEANS OF COMPUTED TOMOGRAPHY

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Abstract: (250 Words)

Computed tomography provides large potential for the quality assurance of micro gears due to its high information density. In this article, an advanced data evaluation strategy based on areal gear parameters, as well as a methodology to determine the task-specific measurement uncertainty by means of computed tomography are presented.

Keywords: micro gear, computed tomography, areal evaluation, measurement uncertainty

1. INTRODUCTION

Micro gears are crucial components in micro transmissions which are used in manifold industrial applications in e.g. medical, automotive, aerospace, industrial automation or robotics. Due to their small size and their important application purposes, their quality requirements are very high. Therefore, both precise measurement systems and sophisticated data evaluation techniques are required to characterize their quality sufficiently.

Most commonly, micro gears are measured by means of a micro coordinate measuring machine (CMM) with a tactile sensor. However, in recent years industrial computed tomography (CT) has been developed to be ready as an alternative measuring technology. It provides the advantage that a very large amount of data points distributed over the entire surfaces of all tooth flanks can be determined by a single measurement.

In order to optimally exploit the potential of CT for gear measurements, an evaluation of the micro gears based on areal gear parameters is suggested, which requires suitable measuring and data evaluation strategies.

Furthermore, for the CT measurements of the micro gears a task-specific uncertainty of measurement has to be determined. In this article, an experimental approach based on an adequate reference standard is proposed.

After a short literature review in section 2, in section 3 and 4 a research approach dealing with these topics is presented. Section 4 concludes with an outlook.

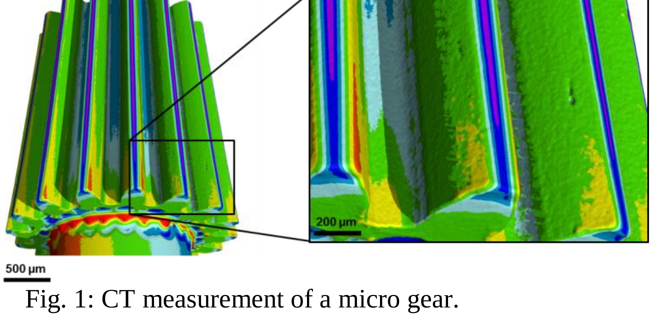

Fig. 1: CT measurement of a micro gear.

2. LITERATURE REVIEW

2.1 Evaluation of Gear Measurements

Traditionally, gear measurements are evaluated by means of line-based parameters (e.g. profile/helix slope and form deviations, pitch deviations), which are standardized according to DIN 21772/VDI 2607 [1-2]. However, this approach systematically neglects deviations distributed over large parts of the flank areas. Yet, due to the large shape deviations of micro gears compared to their size and the low process capability of their manufacturing processes, an areal characterization of the tooth flanks would be particularly suitable for micro gears.

A method for line-based evaluation of CT data has been developed by Haertig et al. [3]. However, as computed tomography naturally provides areal data points, an areal evaluation is very favorable for this measuring method.

Concerning areal gear evaluation, VDI 2607 focusses on a visual representation of selected data points [1]. DIN 21772 only contains a rudimentary definition of the total and form deviation for the tooth flanks [2]. In scientific literature, there are three approaches by Lotze [4], Goch [5-6] and Pfeifer [7], dealing with parametric characterization of tooth flanks based on CMM measurements analogue to conventional line-based parameters.

However, no research work could be found in literature dealing with the special requirements to characterize gears by means of CT measurements based on areal parameters.

2.2 Determination of the Measurement Uncertainty for CT Measurements of Micro Gears

The measurement uncertainty of a CMM measurement can be either determined based on its model equation (analytically according to the “Guide to the expression of uncertainty in measurement” [8] or by simulation according to VDE/VDI 2617-7 [9]) or experimentally according to DIN EN ISO 15530-3 by means of an adequate reference standard similar in material, size and geometry which is measured according to a similar measuring strategy at similar measurement conditions [10].

Several simulative approaches to estimate the measurement uncertainty of CT measurements have been developed, e.g. by Hiller [11]. These, however, are not adequate for the high accuracy requirements of micro gears, as the input factors of the models are not determined in a traceable way.

Various artifacts have been designed to calibrate CT systems based on the experimental approach, e.g. by Neugebauer et al. [12]. These, however, are not sufficient to evaluate the task-specific uncertainty of micro gear measurements, as for gear measurements these artifacts do not fulfill the similarity requirements according to DIN EN ISO 15530-3 [10]. Task-specific uncertainty evaluation of cylindrical geometries has been demonstrated for cylindrical geometries by Bartscher et al. [13] and Schmitt et al. [14] using CMM measurements of the workpiece as a reference. Recently, an artifact to compare tactile, optical and CT gear measurements of different scales has been developed by Haertig et al. [3].

Yet, so far, no valid method has been demonstrated for a task-specific uncertainty evaluation for CT measurements of micro gears.

3. EVALUATION OF CT MEASUREMENTS BY MEANS OF AREAL GEAR PARAMETERS

3.1 Analytical Gear Model

Lotze's analytical gear model for CMMs clearly is the most comprehensive and elaborated approach for parametric quality evaluation of gears of all kind [4]. Thus, most of today's state of the art commercial gear evaluation software is based on its algorithms. Lotze's approach adapted the general methodology of coordinate measuring technique to gear measurements. The basic steps are:

(1) determination of measuring points
(2) approximation of an element of the respective shape
(3) calculation of significant parameters

Lotze's main idea is to model an involute tooth flank by the three parameters base radius r_b, polar angle of the origin of the involute tooth flank Φ_b and helix angle β_b, which are determined for the approximated element (Fig. 2).

The model was designed for tactile gear measurements by a CMM or a gear measuring machine, but can be applied for CT measurements, as well. Yet, this requires some further adaptions to the CT measurement data, which are described in section 3.2.

Furthermore, while the model generally is capable of evaluating gears by means of areal parameters, only line-based parameters according to DIN 21772/VDI 2607 are proposed by Lotze. It, however, can be supplemented by a recent approach by Goch et al. [6], as described in section 3.3.

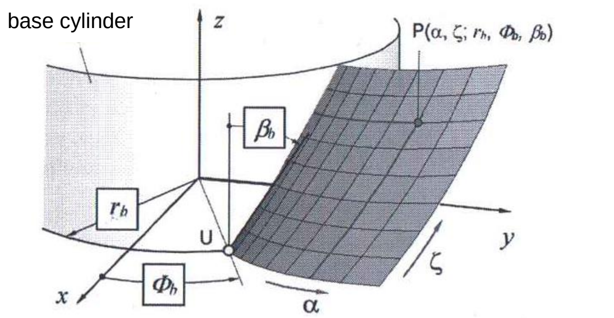

Fig. 2: Analytical model of the involute tooth flanks according to Lotze [4].

3.2 Distribution of Data Points

The measuring strategy of gear measurements by means of CT is to be designed as similar as possible to the well-established CMM conventions. This is important to enhance the universality of the measurement results and to enable a comparison between CT and CMM measurements.

The distribution of the measured data points on the tooth flanks, obviously, has a significant influence on the measurement result. In contrast to conventional tactile measurements of micro gears, where the nominal position of single measuring points can be explicitly adjusted, for CT measurements the location of the data points usually is subject to the edge detection algorithms of the automated measurement software of the CT. Thus, the data points are distributed all over the gear surface in an undefined way.

In a first step the total amount of data points has to be filtered such that the characteristic ranges according to DIN 21772/VDI 2607 (usable profile length L_{AF}, profile evaluation range L_α, gear width L_b, helix evaluation range L_β) can be identified, which characterize the areas critical to the functionality of the gear.

Second, the distribution of the measuring points on a tooth flank within the area determined by L_α and L_β is to be adapted to the desired measuring strategy according to VDI 2607. While in helix direction an equidistant point distribution on the helix length is common standard, three different approaches are specified for the point distribution in profile direction (Fig. 3) [2]:

(1) equidistant point distribution on the roll length
(2) equidistant point distribution on the involute length
(3) equidistant point distribution on the radius

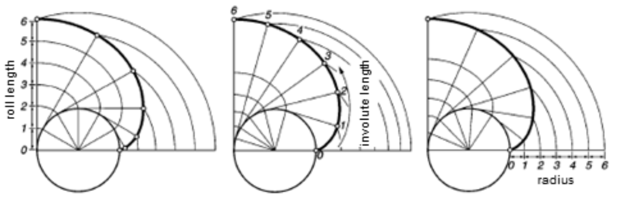

Fig. 3: Equidistant point distribution (1) on the roll length, (2) on the involute, (3) on the radius [2].

Thus, e.g. with respect to an equidistant point distribution on the roll length the point density in tip direction of the tooth flank is much higher than in root direction, as illustrated in Fig. 4. In order to convert the present point distribution of the CT measurement into the desired distribution, a selection, as suggested by Haertig et al. [3], or a combination of data points is generally possible.

For this, a two-step approach is proposed in this article. In the first step, the flank area is divided by a lattice structure with an equidistant distribution in profile and helix direction. For the equidistant distribution in profile direction, one of the three aforementioned strategies is to be selected. In order to achieve a high point density for the respective evaluation strategies, the grid distances are to be minimized. Yet, the lattice distances are subject to the requirement that at least one data point has to present in each field of the lattice. As the lattice distance can be adjusted in profile and helix direction, a multi-criteria optimization problem is to be solved. Fig. 4 shows the generation of a lattice structure based on a simulated point distribution by random numbers.

In the second step, one of the data points within each field of the lattice has to be selected. Alternatively, the calculation of an approximated value based on all of the points within a lattice field could be considered.

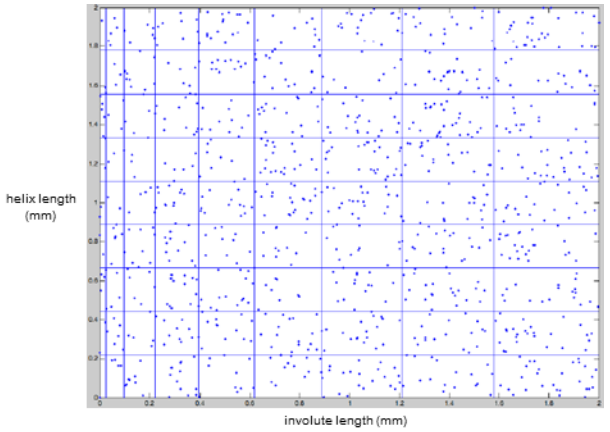

Fig. 4: Lattice structure according to an equidistant point distribution on the roll length.

3.3 Areal Gear Parameters

In contrast to conventional line-based gear parameters, in this article an areal evaluation approach is suggested for CT measurements to exploit its strength of an areal point distribution over the tooth flanks. For this, a combination of the evaluation methods by Lotze [4] and Goch et al. [6] is suitable. First, approximated elements of the involute flanks are to be calculated according to Lotze's analytical model based on the data points within the aforementioned evaluation area given by L_α and L_β. This, particularly, guarantees that the approach complies with the common CMM principle of orthogonal distance regression according to ISO 10360 [15]. Furthermore, the integration into common gear evaluation software is easily possible.

Based on this approximated element, areal parameters are calculated, which closely follow the conventional parameters according to DIN 21772/VDI 2607 (slope, form, total deviation of profile/helix and single/total pitch deviation).

A suitable solution for this provides the adaption of the areal parameters defined by Goch et al. [6] to the analytical model, which is easily possible. Goch et al. consider the profile slope deviation $f_{H\alpha}$ and helix slope deviation $f_{H\beta}$ as the inclinations of the approximated involute plane in profile and helix direction. The profile form deviation $f_{f\alpha}$ and helix form deviation $f_{f\beta}$ are combined to the areal form deviation f_{fa}, as they are identical for an areal point distribution. Similarly, the total areal form deviation F_a replaces the total profile and helix deviations F_α and F_β. For the determination of the total and single pitch deviation, F_p resp. f_p, the involute plane is intersected with the pitch circle.

Thus, a characterization of CT measurements by means of areal parameters can be achieved, easily comparable to conventional CMM measurements. Furthermore, the approach also complies with the rudimentary definition of the flank deviations in DIN 21772 [1].

3.4 Gear Evaluation Software for CT Measurements

In order to be able to apply the aforementioned methods for the areal evaluation of CT measurements, suitable evaluation software is required. A first prototype for this has been developed at the wbk Institute of Production Science. At the current state, it provides the general functionality of the common gear software Involute Pro based on Lotze's analytical gear model. Additionally, the software requires the proposed supplements with respect to the areal evaluation of CT measurement data. The detailed elaboration of this program is subject to further research.

Fig. 5 shows an exemplary visualization for the areal evaluation of the CT measurement of a steel micro gear (module 175 µm, 17 teeth) by means of the software prototype. In this example the raw data points have been analyzed without applying one of the special data evaluation strategies mentioned in section 3.2.

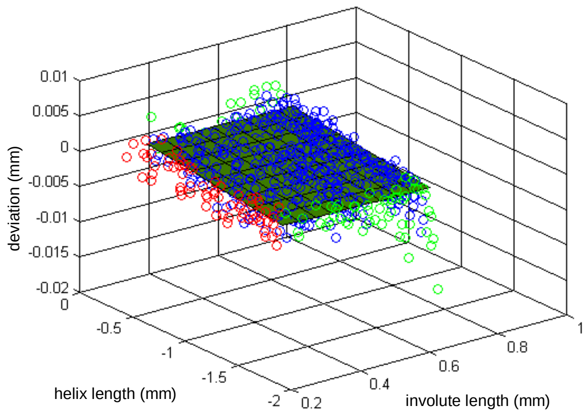

Fig. 5: Approximation of the involute surface based by means of the software prototype at wbk.

4. EXPERIMENTAL EVALUATION OF THE UNCERTAINTY OF MEASUREMENT

4.1 Cylindrical gear standard

At the wbk Institute of Production Science a cylindrical standard (Fig. 6) and an accompanying methodology to experimentally determine the measurement uncertainty for CMM measurements of micro gears were developed [16]. The standard consists of standardized cylindrical steel pins of very high accuracy representing the involute flanks, which are commonly available with diameters in incremental steps of 1 µm. It has been demonstrated that the position and the diameter of the pins can be optimized such that the geometric similarity requirements according to DIN EN ISO 15530-3 are fulfilled [17].

The standard is to be calibrated with a very precise CMM. At the calibration measurements as well as at the measurements with the actual measurement device such as the CT, the standard is to be measured, as if it was a gear. This means that the deviations between cylindrical geometry and involute tooth flank are considered as systematic deviations, which have to be taken into account within the uncertainty budget according to Haertig et al. [18].

Up to now, the capability of the standard for the determination of the measurement uncertainty has only been proved for the line-based profile and helix deviations as well as the pitch deviations based on single data points per tooth flank according to DIN 21772/VDI 2607 [17]. Yet, in theory, the cylindrical design of the standard is perfectly suited for the evaluation of the measurement uncertainty of the aforementioned areal gear parameters, as well.

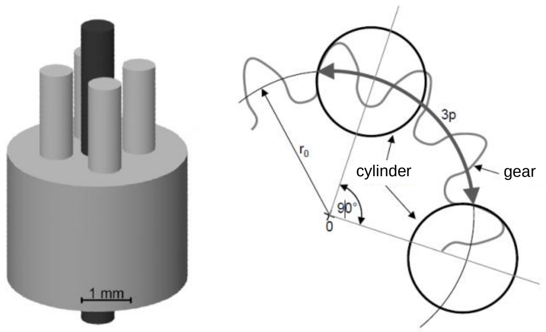

Fig. 6: Cylindrical standard for the experimental determination of the task-specific measurement uncertainty of micro gears [17].

4.2 Evaluation of the measurement uncertainty

The uncertainty of the proposed areal gear parameters determined by means of CT measurements can be evaluated experimentally based on DIN EN ISO 15530-3 [10, 16, 18]:

$$U = k \cdot \sqrt{u_{cal}^2 + u_p^2 + u_w^2 + b^2} \qquad (1)$$

u_{cal} is the calibration uncertainty of the standard determined by the calibrating institution. u_p is the standard uncertainty of repeated measurements of the standard with the CT. u_w is the standard uncertainty between gear and standard due to their material and surface conditions. b is the systematic deviation between the mean value of these repeated measurements and the calibration value of the standard. k is the coverage factor.

In contrast to tactile CMM measurements, where u_w usually can be neglected, for CT measurements it has to be analyzed in detail due to possibly different x-ray absorptions dependent on the material of the gear and the standard. This issue will be further investigated at the wbk Institute of Production Science.

5. CONCLUSION AND OUTLOOK

In summary, in this article a method is proposed to evaluate CT measurements by means of areal parameters based on the analytical gear model by Lotze. Within this approach a method to achieve point distributions according to the different evaluation strategies specified in VDI 2607 is also suggested. Furthermore, a methodology for the experimental determination of the task-specific uncertainty of the gear measurements by means of CT is described.

The proposed topics are subject to further research at the wbk Institute of Production Science.

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