Use of Fringe Projection in the Testing of Precision-Forged Gearwheels

Areal Measurement and Analysis of Cylindrical Gearwheels

K. Meeß, M. Kästner, T. Böttner, J. Seewig, Hannover, Germany

Abstract

The equipment, methods and required precision employed in traditional gear metrology have been based mainly upon the conventional, i.e. metal-cutting, manufacture of gearwheels. However, there is increasing interest, within gear building, for the manufacture of gearing using precision-forging techniques. A production-related testing within the complex process chain of precision-forging requires a fast and areal acquisition of the gearing geometry for process analysis. Hence, a measuring technique based on structured illumination was developed for the testing of cylindrical gears, which dramatically reduces the testing period and provides an areal database for the subsequent analysis. Methods for the evaluation of these areal data are introduced, and in addition the results of optically and tactile derived data are compared.

1 Introduction

Noncutting processes are becoming more and more important for the mass production of high performance gearwheels. Because of their high tact-rates, material- and energy-saving forming processes can partially replace the traditional metal-cutting manufacture. Within these forming processes precision-forging is of particular interest regarding cylindrical gearwheels. Two main-processes can be distinguished [1]:

- the forming process with integrated heat treatment from the forge heat, which provides close to final contour gearwheel blanks,
- the metal-cutting hard finishing process, which provides the final product.

To reliably control such a process, containing few but highly complex manufacturing steps, a production-related inspection of the intermediates before hard finishing is essential. Thus, it is possible to detect wear of the reshaping tools or formal defects as a result of heat treatment. Furthermore, process parameters for the subsequent hard finishing are determined.

The typical process-related geometric errors occurring on the gearwheel blanks, are basically different from the errors resulting from traditional, metal-cutting manufacture of gearwheels.

Through the moulding in the forging die individual gearing errors, like pitch errors and local deviations at the tooth flank, evolve, which necessitates the measurement of all teeth. The conventional line shaped acquisition of the tooth flanks is not appropriate, because these local flaws can only be detected by areal measurements.

The application of a fringe projection system, which works as a 3D imaging device based on triangulation- and phase shift technique, is particularly suitable for a quick and areal acquisition of the optical cooperative surfaces[1], as featured by precision forged gearwheel blanks. With this optical measuring technique the testing periods will be reduced dramatically, compared to tactile measurements.

2 Setup of the Measuring System

A DMD-based (DMD – Digital Micromirror Device) fringe projection system (GFMesstechnik) is utilised for the areal acquisition of the gearwheel blanks. The mode of operation of this triangulation sensor allows for a fast data acquisition of about 10^6 measuring points during one exposure time (approx. 1 – 4 s).

The measuring uncertainty of imaging triangulation sensors is proportional to the length of the diagonal of the measuring field [2], but the use of smaller measuring fields causes a lot of additional measurements to acquire the gearing as a whole. Due to this fact a suitable compromise for the size of the measuring field has to be found to perform gearwheel measurements within an adequate uncertainty and measuring time. Simulations have shown that for gearings with a pitch circle diameter d_m of about 65 – 75 mm a measuring field of approx. 40 x 40 mm^2 has a capable size. However, this specification strongly depends on the parameters tooth number z, module m_n, tooth width b, angle of pressure α and helix angle β.

The setup of the measuring system for the areal acquisition of gearwheel blanks is shown in Fig. 1. All necessary components are integrated into an opto-tactile CMM (Werth Messtechnik), which allows for a high-precision positioning of the fringe projection sensor using the guiding of the CMM. Furthermore an air-bearing precision rotating axis is used to position the workpiece. The rotating axis is assembled on a slewable arrangement to avoid shadowing effects during the acquisition of helical gearings.

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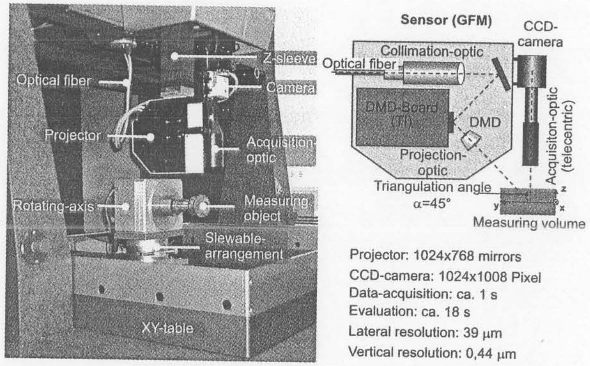
[1] diffusely scattering surfaces

The calibration of the measuring system is done by a multilevel calibration method and is based on a photogrammetric model [3]. This method admittedly shows inaccuracies and non-linearities [3], which are both unacceptable for the determination of the rotating axis and the acquisition of gearings. Hence, it is necessary to determine correction values in subsequent calibration steps by means of measurements on reference objects.



Projector: 1024x768 mirrors
CCD-camera: 1024x1008 Pixel
Data-acquisition: ca. 1 s
Evaluation: ca. 18 s
Lateral resolution: 39 µm
Vertical resolution: 0,44 µm

Fig. 1: Setup of the measuring system and fringe projection sensor

3 Acquisition and Recombination of the Workpiece Geometry

Because of the geometric properties of the gearing and the use of preferably small measuring fields, the acquisition of the workpiece geometry is carried out with respect to the pitch angle. It turned out, that it is reasonable to acquire a number of datasets according to the number of teeth. By this approach many parts of the geometry are recorded redundantly. Hence, areas with high slope, which cause large measuring inaccuracies, can be eliminated from the single measurements. Through this it is possible to optimise both the amount of data and the measuring time.

3.1 Positioning of the Workpiece within the Measuring Volume

As described in Chap. 2, the precision rotating axis is mounted on a slewable arrangement. This allows for a manual positioning of the gearing with respect to the helix angle in the XY-plane. The structured illumination is carried out orthogonally to the normal profile of the gearing, to avoid shadowing effects.

Fig. 2 shows a helical gearing through the optics of the fringe projection sensor. Furthermore the geometry of the gearing and the measuring volume are depicted. Between two illumination sequences, the gearwheel is rotated automatically with respect to the pitch angle.

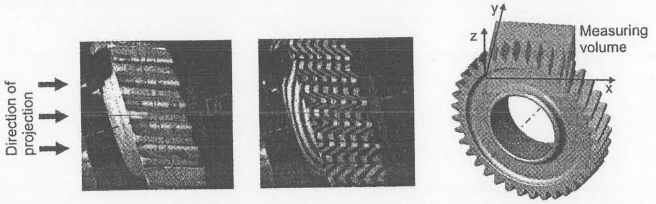


Fig. 2: Positioning of a helical gearing in the measuring volume

3.2 Acquisition and Processing of Partial Views of the Gearing

The acquisition of partial views of the gearing is carried out with the fringe projection sensor by the use of consecutive projections of graycode- and phase shift-sequences. The geometric coordinates are calculated by means of deformation and phasing of the projected fringes.

A single measurement (approx. 10^6 measuring points) is reduced extensively and processed in the following way (see Fig. 3):

- masking of nonrelevant areas,
- masking of areas with high slopes and outliers (gradient-filter),
- elimination of single measuring points through morphological operations.

It has to be pointed out that a single measurement contains information of several partially measured teeth, and cannot be evaluated directly. Tooth flanks, as well as faces and bases, are completed by the recombination of the total geometry from the single measurements.

3.3 Recombination of the Complete Geometry

The recombination of the complete geometry is carried out only by means of geometric transformations of the measuring points. Neither complex matching-operations nor registration processes are accomplished [4]. This approach demands a most accurate determination of the rotating axis, which lies outside of the measuring volume. The rotating axis is determined by measurements on a reference cylinder, whose diameter equals the pitch circle diameter of the measured gearwheel [5].

Fig. 3 demonstrates the recombination of the complete geometry. After the processing of the raw data the number of measuring points is reduced to approx. $2{,}1\cdot10^5$ per single measurement. The complete geometry of the gearing (approx. $8\cdot10^6$ points) is recombined through rotation and translation of the single datasets, with respect to a preliminary workpiece coordinate system, which is orientated on the rotating axis.

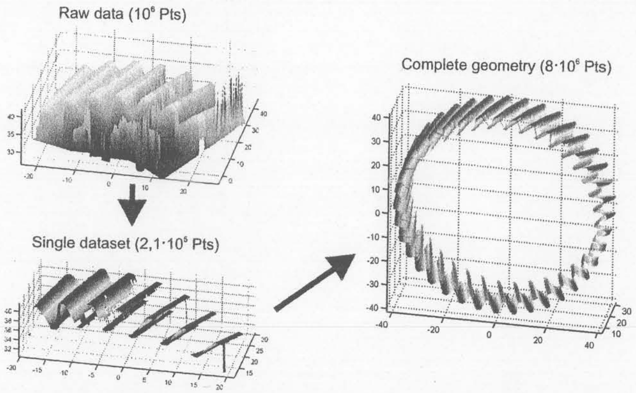


Fig. 3: Recombination of the complete geometry from single measurements

4 Evaluation of the Areal Measuring Data

The advantage of this process is the fact, that the complete geometry of the measured gearwheel can be used to calculate the gearing errors. Thus, it is possible to evaluate the tooth faces and bases additionally to the functional surfaces, e.g. through the analysis of substitute geometry elements. The tooth bases are of particular importance for precision forging. In that area the highest powers take effect on the forging tool and cause most of the abrasion. The evaluation of the functional (involute) surfaces is demonstrated in the following. These surfaces are extracted from the complete measured geometry for fitting and evaluation.

4.1 Reference Generation by Fitting of the Measured Geometry

Before the actual evaluation, the complete measured geometry has to be aligned on a reference geometry. On the one hand the conclusive workpiece coordinate system is determined this way, on the other hand the fitting allows the separation of geometric distortions and positional errors through incorrect chucking or erroneous position of the bore as reference. The fitting process is carried out with the involute surfaces of the gearing. Aim of this procedure is the definition of a virtual gearing axis as a reference for the determination of gearing errors.

The alignment of the measured data $\vec{p}_{i,mess^*}$ is carried out alternately both rotatory and translatory referring to the point of origin. The objective function for the minimisation of the squared length of the single deviation vectors $\vec{a}_{i,evol}$ according to the L_2-Norm has the form:

$$f_{ziel} = \sum_{i=0}^{n} \left|\vec{a}_{i,evol}\right|^2 \rightarrow \min \qquad \text{[Eq.1]}$$

The following iteration rule results for the rotatory alignment [6]:

$$\vec{\varphi} = \frac{\sum \vec{p}_{i,mess^*} \times \vec{a}_{i,evol}}{\sum \left|\vec{p}_{i,mess^*}\right|^2} \qquad \text{[Eq.2]}$$

The translation vector $\vec{v}$ is determined by the means of the single deviation vectors $\vec{a}_{i,evol}$:

$$\vec{v} = -\frac{1}{n} \sum \vec{a}_{i,evol} \qquad \text{[Eq.3]}$$

This process is extremely robust and mostly converges after few iteration steps. The calculational effort is manageable and the process can be applied on large amounts of data.

4.2 Presentation of the Deviations

The large amounts of measuring data must be presented comprehensively for the evaluation. For the line shaped analysis of gearing tolerances [7] standardised flank- and profile line records with accordant characteristic values were established [8]. The evaluation of the areal gearing measurements is not subject to any standardisation. Due to the fact that it was not possible to acquire areal gearwheel measuring data with high point density economically, so far, only few approaches were published [9, 10].

At first a visual assessment of the areal measuring data is carried out. The deviations of the single measuring points are determined with respect to a reference involute and presented like in Fig. 4. The pictorial illustration (Fig. 4, right) is generated by interpolation of the original data into an equidistant point grid.

This kind of presentation is very applicable for a visual evaluation of the deviations. Particularly, if several deviation charts are merged to a "deviation atlas", both individual and systematical errors can be detected (Fig. 5).

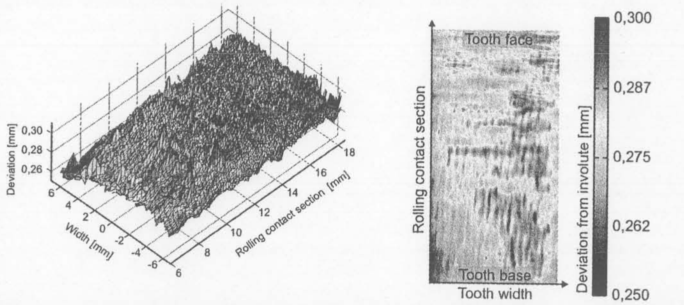


Fig. 4: Transformation of the areal gearing errors from a 3d diagram to a pictorial illustration

A best fit plane is calculated from the original data for the quantification of gearing deviations. The distance of this plane from the point of origin complies with the mean deviation of the tooth thickness and the material allowance, respectively. The position of the plane provides information about the mean deviations of the tooth flanks and profiles, based on the tooth width and the rolling contact surface.

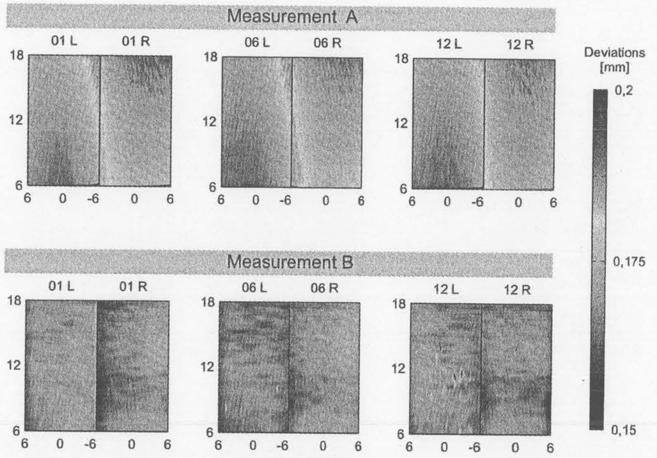


Fig. 5: Pictorial representation of the areal gearing deviations with systematical (measurement A) and individual (measurement B) deviations

5 Comparison with Tactile Reference Measurements

The described experimental setup allows for areal measurements of optically cooperative gearings and provides the necessary database for the evaluation. To estimate the accuracy of this technique, tactile reference measurements are carried out and compared to the optically derived data.

5.1 Reduction of the Areal Measuring Data to Profile- and Flank Lines

For a comparison of tactile and optical measurements it is necessary to reduce the areal geometry data to standardised line profiles. Measuring points, that lie directly near the profile- or flank lines, are projected onto these lines. Furthermore, equidistant points are generated on the tooth profiles and the tooth flanks through linear interpolation, and are converted into the GDE-data format [11].

The comparative measurements are carried out on a tactile gearwheel measuring machine (ZMC 550, Zeiss). The measuring data of the flank- and profile lines are also converted into the GDE-data format. The determination of tooth thickness, pitch deviations, radial deviations, and profile- and flank line deviations is accomplished with a special gearwheel analysis software [12].

5.2 Results of the Comparison

The comparative measurement of a precision forged gearing is illustrated in Fig. 6. Radial and pitch deviations were calculated with the software through virtual touch on the base of profile regression lines [13]. The difference between tactile and optical measurements constitutes approx. 2 – 3 µm in the mean. The differences concerning the profile deviations are slightly larger with approx. 5 – 10 µm. On closer examination of the profile deviations a systematic positional error stands out, which is caused by the different generation of the reference system. The gearing axis (reference) is determined from the line profile in case of tactile measurements, and from the areal measuring data in case of optical measurements. A new alignment of the reduced areal measuring data is not accomplished. The comparison of the characteristic values for the profile deviations [8] provides significant differences, due to the amount of noise on the optical measuring data.

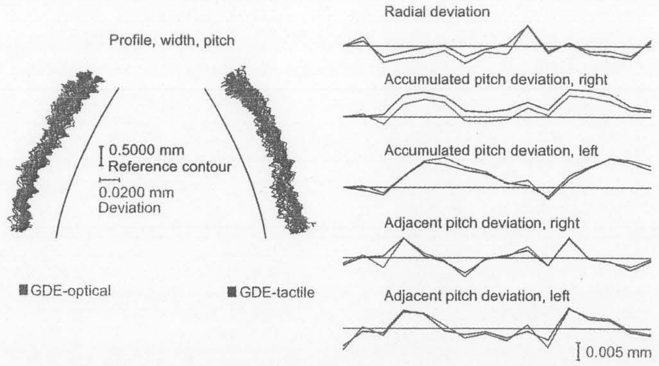


Fig. 6: Line-based evaluation and comparison of an optical and a tactile gearwheel measurement ($z = 16$, $m_n = 4.5$ mm, $b = 16$ mm, $\alpha = 20°$, $\beta = 0°$)

The asserted maximum differences of about 10 µm are a prove for the correctness and the application of this optical measuring technique. The requirements on the optical measuring technique for the testing of precision forged gearwheel blanks are satisfied, even though the determined differences give no conclusion about the measuring uncertainties. These results have to be verified by measurements on reference gearwheels.

6 Conclusion

The introduced optical measuring technique represents an approach to accomplish the general interest in economical and areal gearwheel measurements. During this process the beneficial optical properties of the precision-forged gearwheel blanks are utilised. Furthermore, this measuring technique is assignable to every optical cooperative cylindrical gearwheel. Compared to tactile measurements the measuring time is reduced dramatically, while the density of information is highly increased. The measurement of gearwheel geometries by means of structured illumination can be applied economically within industrial process chains and provides valuable information on process-related errors, through the topological analysis of gearing deviations. The limits of this technique are clearly reached with the evaluation of finished gearwheels, since the measuring inaccuracies are much higher compared to tactile measurements. In addition, it is not possible to acquire standardised profile- and flank lines with this optical triangulation technique, as well as with other areal measuring methods.

There is huge demand on the development of areal evaluation techniques of gearwheel measurements and the calibration of the measuring system, but the attained results are greatly encouraging.

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A new generation of gear measurement software with CAD kernel

Gear Pro

D. Imkamp, Oberkochen, Germany

Abstract:

Gear measurement on coordinate measuring machines (CMM) is almost as old as coordinate metrology itself. For these gear measurements, different software products were created and upgraded on an ongoing basis. Gear measurement software now offers a wide selection of functions for measurement and evaluation. However, very often the progress in electronic data processing such as CAD-data usage and graphically interactive user interfaces were not fully utilized. With GearPro, Carl Zeiss IMT (Industrial Metrology) sets a new standard for a new generation of gear software. For the very first time the GearPro software systematically utilizes state-of-the-art technologies [1]. GearPro Bevel is used to measure bevel gears. Spur gears are measured with or without a rotary table using GearPro Involute. A version for worm gears is under development.

Gear Measurements on CMMs

Gear measurement tasks are common measuring tasks for CMMs. Especially CMMs with an active scanning system are very suitable for gear measurement. With their active scanning probe they are able to position the probe exactly to hit the correct measuring points. Simultaneously they could measure very precise because the large deflection range of the probe requires only small tracking distances [2].

A CMM can be equipped with a rotary table as fourth axes. Therefore a CMM with an active scanning system is a very good gear measuring machine. Furthermore it can be used to measure other kinds of work pieces like housings or bearings. Due to their abilities and their high flexibility a large number of CMMs is used for gear measurements (figure 1).