In-Process Quality Control in Gear Wheel Manufacturing by the means of Best-Fit Gear Wheels

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Abstract

A non-contact, optical CMM is introduced that allows for considerably faster measurements than a conventional, tactile CMM. It is shown how this technology can be exploited enabling in-process inspections of gear wheels, and other rather complex (axially symmetrical) parts in one or more 2D cross sections. The (2D) traverse profile of a gear wheel serves as an example for process optimization and quality control. It is demonstrated that one can find a best-fit (substitute) gear wheel from the traverse profile of a precision forged (semi-finished) gear wheel by the means of orthogonal distance regression (ODR). From the best-fit gear wheel one obtains a set of parameters that can be used to establish control charts for optimizing preceding production steps (e.g. forging). Also, the set of parameters allows for feedforward quality control of subsequent production steps (e.g. pitch-grinding).

Introduction

One of the main tasks in the field of mechanical engineering is the transmission and transformation of torque and (input) speed. It is mostly accomplished using gear boxes with external or internal spur, helical, or even double helical gear pairs which are mostly manufactured in rather time consuming metal-cutting processes. Therefore, faster processes (e.g. forging of gear wheels, cam shafts, crank shafts, and so on) are demanded especially in mass production such as in automotive industry that, furthermore, at the same time provide parts with decreased tolerances and increased accuracy. This, in general, is the subject of investigations into the "process chain for the manufacturing of high performance parts" (SFB 489) at the University of Hanover. In particular, the accuracy of gear wheels is improved by an enhanced manufacturing process (precision forging in a closed forging die) as well as by numerical optimization procedures. However, one of the premises for optimization is the capability of taking accurate (in-process) gear wheel measurements. In the following both the optical cylinder coordinate measuring machine (CMM) that is set up at the Institute for Measurement and Control Engineering and the optimization procedures are introduced. [6]

Optical cylinder CMM

Basically, only one rotation axis and only one distance sensor are sufficient for taking traverse profile (2D) measurements in cylinder coordinates of gear wheels of the same size. However, taking measurements of a variety of parts (i.e. gear wheels of different size or shape) and in several cross sections (traverse profiles) (thus, generating a 3D measurement grid of the specimen) requires a more flexible measuring technology such as provided by CMM. However, conventional CMM consisting of three translation axes (X, Y, Z) and a tactile probe can only provide a low measuring point density involving a rather long measuring time period when it comes to very complex geometries (e.g. gear wheels), thus, prohibiting in-process inspections. Consequently, in-process gear wheel measurements necessitate a CMM with two (R, Z) or more (X, Y, Z) translation axes and one (additional) rotation axis (C) as well as a non-contact (i.e. optical) probe replacing or supplementing the conventional tactile probe. [6]

The cylinder CMM is equipped with an optical distance sensor the measuring principle of which is based on conoscopic holography. The basic setup of the conoscopic sensor is displayed in figure 1.

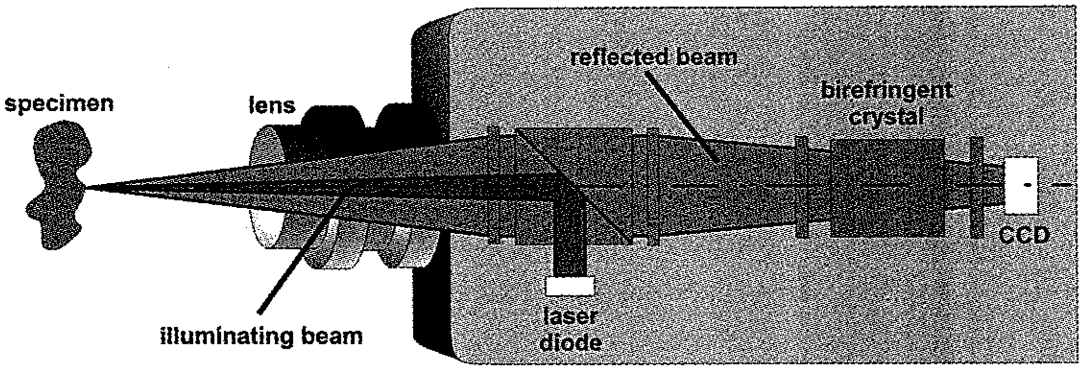

Fig. 1: Basic setup of the conoscopic sensor (from [2])

A beam splitter and an appropriate lens are used to focus the laser beam emitted from a laser diode on the surface of the specimen. The reflected beam is manipulated in essence by a birefringent crystal. The birefringent crystal cleaves the reflected beam into an ordinary and an extraordinary beam which cause a high contrast pattern on the CCD depending on the distance of the specimen. [1]

The advantage of the conoscopic sensor over other optical sensors using various different measuring principles (e.g. triangulation) is the fact that both the illuminating beam and the reflected (i.e. measuring) beam have exactly the same optical axis. As a result, almost no restrictions (e.g. triangulation angle) apply as far as the direction of measuring is concerned and, therefore, measurements can be taken even at angles of up to 85° (grazing section) in any direction from the normal direction of the measured surface.

Table 1: Specification of the conoscopic sensor using different lenses [1, 2]

vertical				lateral
focal length	precision	working range	standoff	resolution
50 mm	6 µm	8 mm	42 mm	15 µm
75 mm	10 µm	18 mm	65 mm	25 µm

The specification of the conoscopic sensor using two different lenses (with a focal length of 50 mm and 75 mm) is given in table 1. The vertical direction is parallel to while the lateral direction is perpendicular to the optical axis of the probe. Note that the lateral resolution is estimated by the manufacturer from a fine "record notch" pattern [1, 2].

The three speed (10°/s, 30°/s, 60°/s) rotation axis of the cylinder CMM is equipped with a high precision rotary encoder using a solid measure with 36,000 physical pulses per one revolution. With subsequent fourfold evaluation and fivefold interpolation a total resolution of 0.0005° (1.8 arcsec) is retrieved.

Resolving cylinder coordinates

Any measuring data in cylinder coordinates comprises the information of the radius at a certain angle. Since the conoscopic sensor is a mere distance sensor, the distance information must be converted into radius information by taking a reference measurement from a cylinder normal, for instance. Due to the much better accuracy and, therefore, negligibly small inaccuracy of the cylinder normal compared to the conoscopic sensor the overall precision for absolute *radius measurements* remains the same.

Moreover, the calculated radius and the angle obtained with the rotary encoder must be merged to proper cylinder coordinates. For this purpose an external trigger is used firing a signal every so often to the rotary encoder and the conoscopic sensor prompting both measurement readouts. The external trigger frequency must be less than the measuring frequency of the conoscopic sensor of 850 Hz corresponding to an integration time of the CCD of 1.2 ms. At a typical rotational speed of the C axis of the cylinder CMM of 10°/s this is

equivalent to an angle of 0.012° or about 8 µm assuming a radius of 40 mm, which is the typical average radius of gear wheel features to be measured.
The worst case triggering scenario is excessively displayed in figure 2.

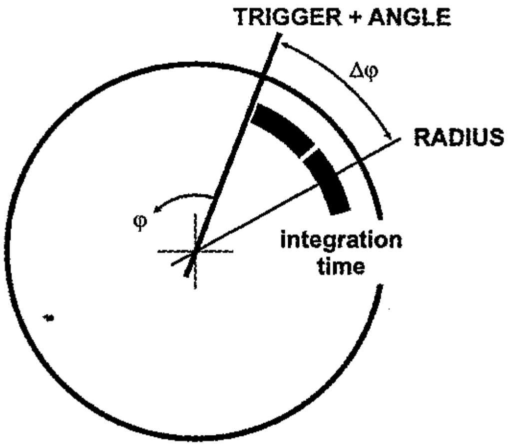

Fig. 2: Worst case triggering scenario

The worst case scenario occurs when the trigger prompts the angle measurement without any delay at all but in contrast prompts the radius measurement slightly before the most recent radius measurement is accomplished, thus, causing a delay that is equal to the integration time of the CCD. Assuming that the radius measurement obtained by CCD integration resembles the radius at the middle of the integration time, as a result, the radius measurement lags behind the angle measurement by an angle $\Delta\varphi$ of 0.006° up to 0.018° without any correction. Eventually, this leads to an overall uncertainty of the angle of ±0.006° where a potential delay of the angle measurement (max. 0.0005°) is negligible. This figure is equivalent to about ±4 µm again assuming a typical average radius of gear wheel features to be measured of 40 mm.

As described above (see table 1) the lateral resolution of the conoscopic sensor is 15 µm or 25 µm, respectively, depending on the lens used, which is a multiple of the uncertainty of the angle. However, this value is only estimated by the manufacturer from a fine "record notch" pattern in perpendicular direction to the optical axis of the conoscopic sensor. Hence, the actual lateral resolution may vary depending on the inclination of the measured surface, i.e. the angle between the normal direction of the surface and the optical axis of the conoscopic sensor (≤ 85°), as well as other surface characteristics such as the reflectivity, for instance.

Nevertheless, as can be seen from the worst case triggering scenario, the limiting factor is the lateral resolution of the conoscopic sensor.

Reference gear wheel

Having obtained in-process gear wheel measurements, the measurement data must be processed and evaluated involving a reference gear wheel. Multiple opportunities of establishing reference gear geometries (depending on the kind of gear, e.g. E-, S-, cycloid, circle gear etc.) exist which are illustrated in this section.

The most common gear is the E- (involute to a circle) gear that is specified by the gear parameters module (*m*), tooth number (*z*), angle of action (α), helix angle (β), addendum modification coefficient (*x*), and clearance coefficient (c^*). In this case the usable flank is an involute to a circle. The gear wheel is completed by the crest, which is a section of a circle, and the fillet and bottom land, which can be easily approximated by an ellipse as described in [7]. For enhanced performance of the gear wheel often profile modification is used which is similar to the material allowance required for the grinding process (e.g. pitch-grinding) of precision forged gear wheels in gear wheel manufacturing. Different types of material allowance exist the most important of which are equidistant, linear, quadratic (also referred to as comma-shaped), and crowned material allowance. An excerpt is given in figure 3.

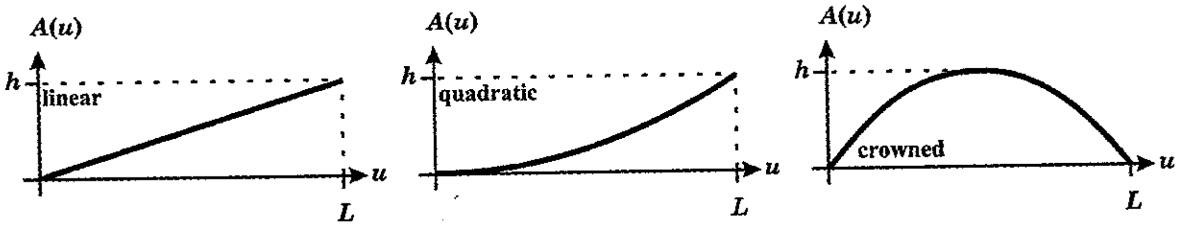

Fig. 3: Profile modification | material allowance [4, 7]

The profile modification | material allowance *A*(*u*) with a reference height *h* is the additional material in the normal direction of the surface at a certain point *u* on the usable flank, where *L* is the total length of the usable flank [4, 7]. Likewise, other profile modifications such as tip relief that are not spread over the total length *L* of the usable flank but instead are confined to a certain area of the profile (e.g. the tip of the flank) can be allowed for in a similar way. If it may be required to use more than only one type of profile modification or material allowance, it is also possible to superpose several by simple summating them.

Alternatively, the reference gear geometry (e.g. of an S- or circle gear) can be virtually any implicit function describing either a tooth or a tooth space inclusive of the crest, fillet, and bottom land [5]. Moreover, if the exact mathematical description of the gear is unknown but a set of points – again describing either a tooth or a tooth space inclusive of the crest, fillet, and bottom land – exists, which is frequently true as it can be used for CNC machine control in gear wheel manufacturing, this set of points itself can serve as a reference or could be easily used as supporting points for linear splines serving as a reference [7].

In any case, however, one restriction applies regarding the reference gear geometry. Any kind of undercut must be strictly avoided, which is especially true for the fillet of the tooth profile, where often undercut exists due to root relief intended by the design engineer or cutter interference during the manufacturing process. Otherwise (i.e. with undercut) it is impossible to calculate a best-fit gear wheel. Yet the avoidance of undercut regarding the reference gear geometry is not a hindrance, because exactly the same restrictions apply to the subsequent grinding process (e.g. pitch-grinding) – only any meshing interferences of the engaged gear wheel have to be avoided.

Best-fit gear wheel

Having knowledge of the reference gear geometry, a best-fit gear wheel for the gear wheel measurement data (traverse profile) can be calculated employing optimization algorithms based upon the orthogonal distances of the measuring points from the reference gear geometry. The orthogonal distance of a measuring point from the reference gear geometry can be calculated easily as described in [4, 5, 6]. Moreover, [4] also addresses in detail the incorporation of profile modifications (material allowance).

The orthogonal distance regression (ODR) is accomplished complying with one of a variety of optimization criteria such as least absolute values (L1), least squares (L2 or LS – Gauss), minimum zone (L_∞ or MZ – Tschebyscheff), minimum circumscribed (MC), or maximum inscribed (MI). The appropriate optimization criterion has to be chosen taking into account both whether an internal or external gear wheel is manufactured and the manufacturing process applied that is to be controlled. From this optimization process a set of estimated parameters is resolved which comprises the position of the center and orientation of the gear wheel as well as either its size, specified by its newly calculated module, or the modified equidistant material allowance. [5, 6]

Quality control

Having resolved the set of estimated parameters from the optimization process, it can be used for feedforward quality control of subsequent production steps as illustrated in figure 4. The misalignment of the hole of the forged part and the bore of the finished part as well as the non-uniform material allowance can be seen. At first, the part geometry is obtained with the optical cylinder CMM. Then the CMM data is fed to the optimization algorithms based upon the material allowance that calculate the position of the center of the gear wheel which is equivalent to a displacement vector. The displacement vector is transmitted to the chuck of the lathe that is equipped with sensors and actuators. A stacked piezo-electric actuator is used to accomplish the fine positioning of the forged part ensuring proper alignment of the forged part for the machining of the bore. The result is a uniform distribution of the material allowance for subsequent production steps such as pitch-grinding. [6]

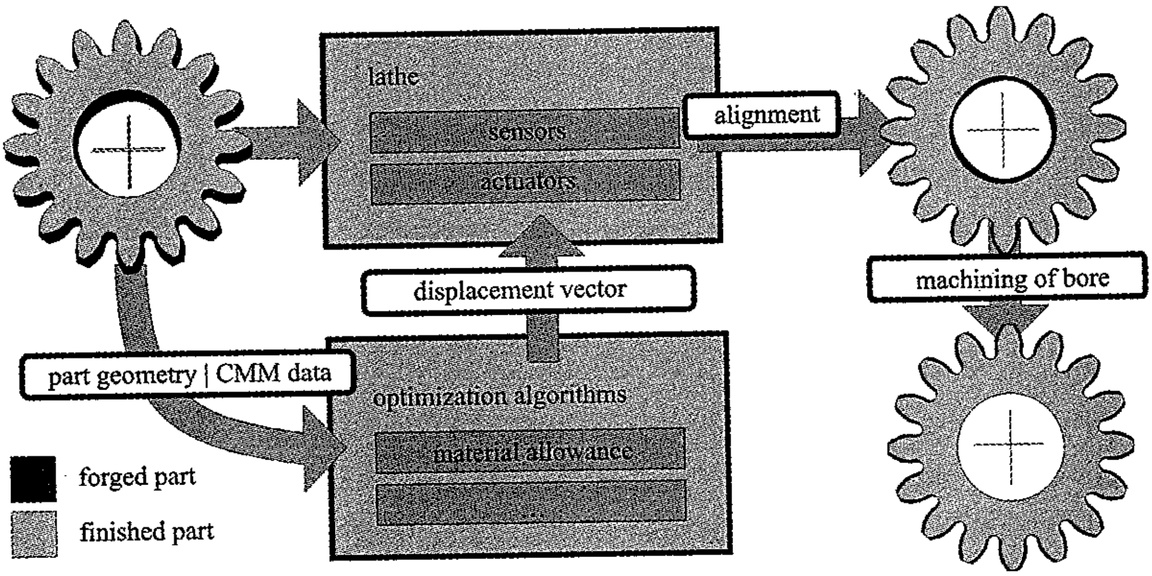

Fig. 4: Process optimization by means of feedforward quality control [3, 6]

This procedure of feedforward quality control helps to minimize the material allowance of precision forged parts required for subsequent grinding processes. On the one hand, limited resources such as raw material and energy are spared, thus, simultaneously reducing the environmental impact while, on the other hand, by these quality improvements the amount of failure parts in the manufacturing process is reduced.

Likewise, a similar procedure can be used for the evaluation of individual features of a gear wheel (e.g. an individual tooth space or an individual tooth). In this case optimization procedures can also be used to calculate multiple sets of estimated parameters for these individual features. However, the sets of estimated parameters of individual features correspond to previous production steps such as precision forging. For example, the wear of the forging die (the die could be seen as an internal gear wheel), i.e. the wear on the section of the forging die (e.g. a tooth) that corresponds to the individual feature of the forged external gear wheel (e.g. a tooth space), could be monitored employing control charts based upon one or more of these sets of estimated (individual) parameters. Hence, one can tap a very powerful means easily enabling preventive or performance based maintenance. [6]

This procedure of feedback quality control helps to maximize die life and, thus, reduces tool and tooling costs while, at the same time, by these quality improvements again the amount of failure parts in the manufacturing process is reduced.

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