Fast In-Line Quality Assurance of Gearwheels

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Abstract

This paper shows the developed measurement system for the fast in-line (lathe integrated) measurement of gearwheels. The measurement equipment consists of a fast and high precision laser distance sensor, the synchronization and the PC-based data processing.
Using different methods in data processing, clamping errors due to material allowance, eccentricity, distortion, geometry variations (deformation) and other possible errors can be detected before starting the cutting process. Additionally, methods to compensate the detected eccentricity are shown in this paper.

Introduction

The common manufacturing process of automotive transmission gearwheels consists of different machining steps. At first, raw parts are forged from round stocks, the next machining process is the manufacturing of the toothing, often using a hobbing machine. At this process step, there is still material (allowance) on the reference geometry such as the central bore or the flanks.
The following process is the heat treatment, usually a case hardening process.
The final manufacturing steps are the hard turning of the central bore and the grinding process of the flanks, where the central bore is used as a reference to assure a good quality of the radial run out (Fig. 1).

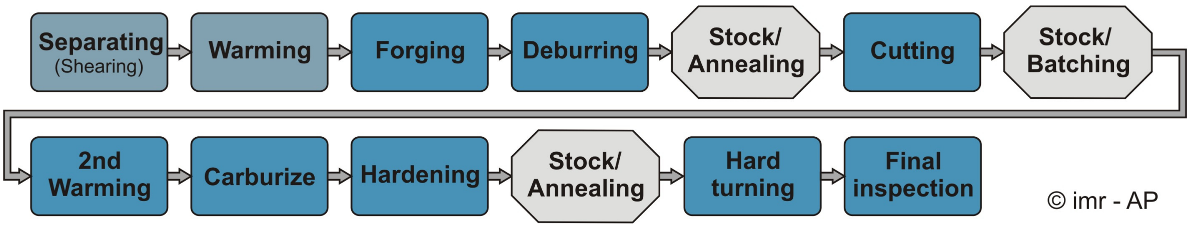

Figure 1: Common manufacturing process of automotive gearwheels

The common quality assurance in the manufacturing process of gearwheels is based on production-related tactile measurements using coordinate measurement machines (CMM).
Newer developments in measurement technologies introduce optical measurement techniques such as fringe projection or laser triangulation for production-related gearwheel measurements.
The common disadvantages of production-related measurements are long cycle times and the additionally needed space for the measurement laboratories. Due to this, the quality assurance is limited to random testing during the manufacturing process and usually a complete final inspection of the fully manufactured gearwheels.

Motivation

In order to find new techniques in manufacturing, the Collaborative Research Centre 489 (CRC 489) called “Process chain for the production of precision-forged high-performance components” has been initiated at the Leibniz Universität Hannover. As sample components for precision-forged gearwheels, pinion shafts and crankshafts have been chosen. The transfer research project T4, called „Adaptronic precision positioning system in chucks for machine tools”, was initiated to research a new manufacturing and inspection technology in cooperation with industrial partners [1].
The objective of this research project is the in-line inspection and correction of conventional manufactured camshaft gearwheels (Fig. 2). These camshaft gearwheels get distorted during the case hardening process. Because of this distortion, clamping errors in the hard turning process of the central bore occur and the resulting eccentricity of the clamped gearwheel leads to an eccentricity of the central bore again. The central bore is used as a reference in the following grinding process, so the eccentricity leads to a low quality as well as scrap of the gearwheel.

	German VDI 3960	English
Gear tooth system	Involute	
Number of teeth	55	
Modul	1,75 mm	68,89 thou
Pressure angle	15°	
Helix angle	0°	
Reference diameter	96,25 mm	3,647 in
Tip diameter	101,2 mm	3,984 in
Root diameter	90,28 mm	3,554 in

Figure 2: Camshaft gearwheel

The quality assurance of the manufacturer uses tactile CMMs for the complete final inspection of the manufactured gearwheels. Due to this production process, fully manufactured gearwheels are separated cause of their low quality.
To improve the quality of the gearwheels new technologies concerning in-line quality assurance are needed. Most interesting process step is the hard turning of the central bore, where the reference for the following grinding process is made. Common tactile methods can not reach the needed short cycle times in automotive related gearwheel manufacturing. In order to avoid low quality, a fast measurement technology and data processing is needed.

Measurement Equipment

The measurement equipment consists of an optical distance sensor, the synchronization electronics and the data processing.
The fast and high-precision conoscopic laser sensor measures the workpiece geometry in a transverse plane during one revolution. The co-linear principal (the lighting of the workpiece and the capturing of the reflected light are in one axis) of conoscopic holography allows measurements at angles of about ± 85 degrees orthogonal to the optical axis of the sensor. This great advantage compared to conventional optical principles, such as triangulation, allows the measurement of the complete gearwheel including its functional elements, the flanks.
Manufacturer of this optical sensor is Optimet optical metrology Ltd. The stand-off and the possible resolution can easily be changed by using different accessory lenses.

The accuracy of the sensor basically depends on the chosen lenses. Other factors are the optical cooperativity of the workpiece-surface, the parameter adjustment of the sensor and finally the angle of the laser beam to the workpiece surface. In the used test setup, the absolute accuracy with the chosen lens “50 extended“ is specified with better than 6 μm (0.236 thou) with a reproducibility (1σ) << 1 μm (0.039 thou). This lens provides a stand-off length of approximately 85 mm (3.34 in) and a measuring range of about 8 mm (0.315 in) [2].
The specification of the accuracy is based on orthogonal measurements, e.g. the angle α between the optical axis and surface’s normal is zero. In order to quantify the uncertainty of measurement in various angle positions, tactile reference measurements using a calibrated plane normal were done (Fig. 3).

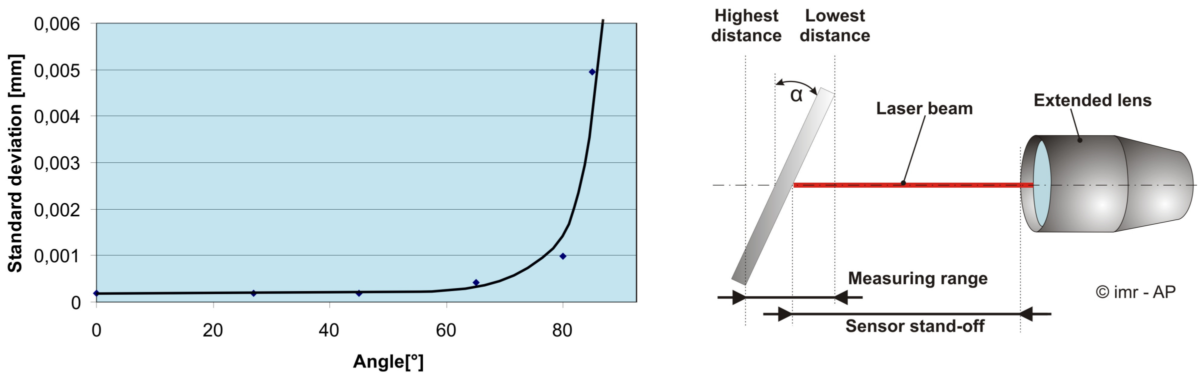

Figure 3: Sensor definitions and uncertainty-angle diagram

The diagram shows, that the uncertainty of the optical measurement strictly depends on the angle α between the optical axis and surface’s normal. Thus, the capturing of flanks, especially on gearwheels with a small pressure angle, is more insecure than the tip circle or the root circle (cf. figure 5).
In additional tests, a newer version of the ConoProbe was used. This version of the optical sensor provides an increased measuring frequency (15000 Hz to 3000 Hz).

The synchronization electronics connects the rotary encoder of the machine spindle to the industrial PC and the conoscopic sensor. The measured distance data and the angle information of a rotary encoder are used in combination to reconstruct the geometry of the gearwheel. Usually, incremental rotary encoders with TTL signal output are used to control the revolutions of the machine spindle. In addition to that, sinusoid rotary encoders can be used with the interconnection of digital interpolation electronics. The data processing of the incremental signal is provided by a National Instruments counter/timer card. This PCI card allows a four-quadrant encoding of the TTL-signals, which means both edges, rising and falling, of each 90 degrees shifted signals (channel A and channel B) are counted.
Depending on the rotation direction, the counter value is incremented or decremented. The third channel, called Z channel, provides the opportunity for a reset of the counter and is also used for an absolute reference during one revolution.
In the test setup, the counter/timer card is mounted into a conventional PC with Ethernet connection, which is used for the data connection to the optical sensor.

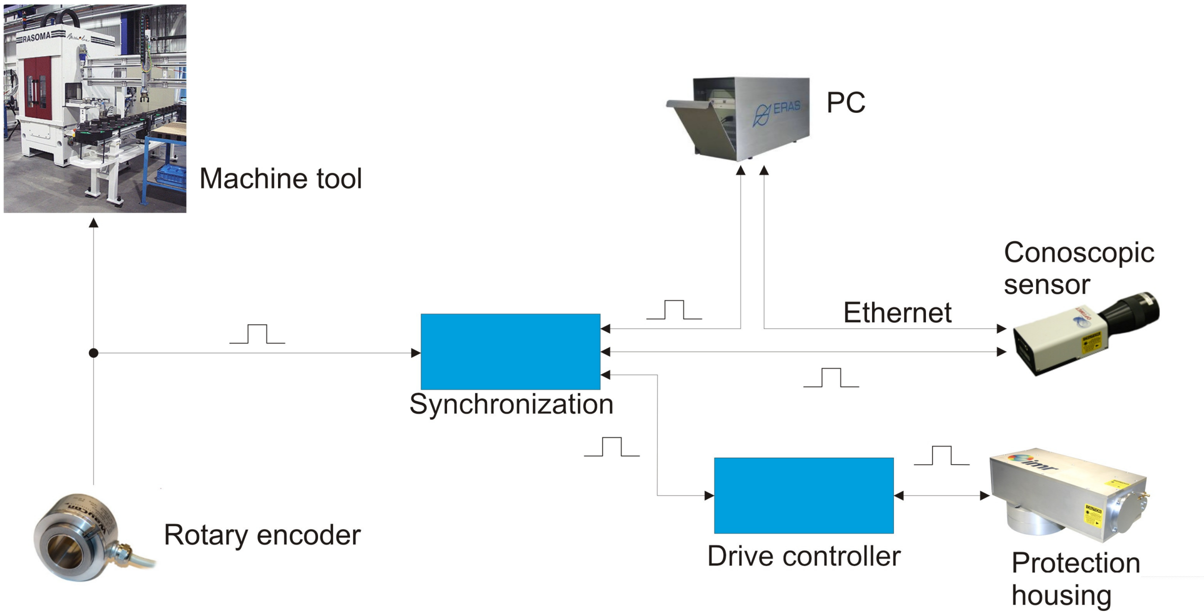

Figure 4: Communication structure of the gearwheel measurement system

The digital I/O channels of the counter/timer card are also used to control the motorized protection cover (shutter) of the sensors housing.

Algorithms

The data processing consists of three parts: The preprocessing of the measured data (filtering), extraction of functional geometry information and the post processing.
The optical sensor offers the opportunity to use information about the signal quality, amount of captured light and saturated CCD-pixel for filtering abroad the distance data transmitted. A typical signal to noise ration – radius diagram of a gearwheel measurement is shown in figure 5.

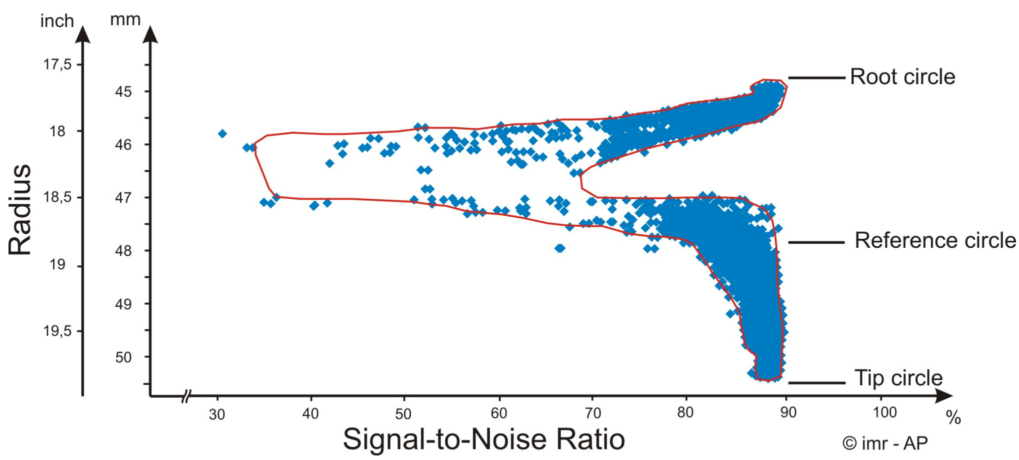

Figure 5: Signal to noise ration (SNR) of a camshaft measurement

This information is used to select the measurement points captured with a high quality.
Two characteristic geometry elements, the tip radius and the root radius, can be detected with a high signal to noise ratio. The functional geometry, the flanks, is hard to capture at the steep base circle. According to this fact, two simple and robust algorithms had been

developed. The first algorithm extracts the root radius data, the second one the tip radius. Depending on the manufacturing process, this algorithm can be used. Concerning the camshaft gearwheel, the root radius is manufactured in the hobbing process of the toothing. Thus, this algorithm is the common method for fast characterization of the gearwheel.
Other important information concerning the quality assurance of gearwheels is the pitch. Especially the tooth thickness is important due to allowance variations in the manufacturing process and can detected with a transverse plane measurement.

Last step is the post processing of the extracted data. Most limiting factor are the required short cycle times in automotive related gearwheel manufacturing. In order to get information like the eccentricity, fast algorithms are needed.
Common post processing algorithms are iterative fitting algorithms, consisting of a minimization norm (e. g. Gaussian norm) and a minimizing algorithm (e. g. downhill-simplex algorithm) [3]. Because of the iterative character, deterministic short cycle times can not be reached.
In order to characterize eccentricity and distortion, new spectral analytic methods are established.

Results

The simplest configuration of a lathe integrated, in-line quality assurance of gearwheel consists of the conoscopic laser sensor and a PC for the data processing. The Sensor is triggered by the incremental encoder of the machine spindle. With this configuration, the distortion and eccentricity can be detected. Without angle information, the correction of eccentricity is not possible.
Common configuration of the test setup is the described system plus the integration of the counter/timer card to get angle information. In this configuration, the algorithms concerning the reference circle and the tooth thickness can be used.
The last configuration was developed for the use in automated manufacturing processes. The quality assurance is combined with a Profibus data communication between the data processing and the lathe. The counter/timer card controls the protection cover and the CNC-program of the lathe is changed to use the measurement equipment.
All configurations can be used in relative and absolute measurements. The algorithms can be used to calculate with the measured distance (relative) or by using absolute radius values. To use this configuration, a high precision cylinder standard with known radius (diameter) must be measured to get an absolute distance reference once. The measured relative data can be easily converted by using this reference.

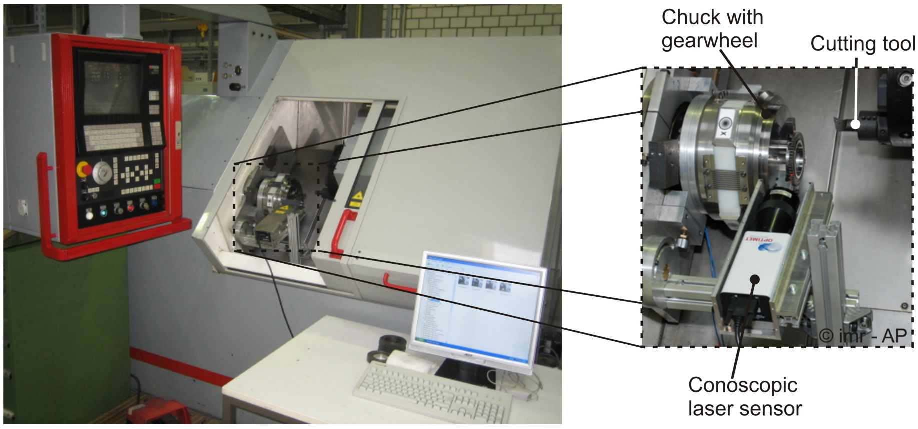

Figure 6: Sensor integration into a lathe

In order to reach deterministic short cycle times, a discrete Fourier transform (DFT) of the extracted data is used. The different oscillations are used for the characterization of the gearwheel. The simplest information is the eccentricity, which can be quantified with the basic oscillation. The principle is shown in figure 7. Common frequencies for distortion are the second and fourth oscillation. Using three jaws chucks, clamping errors can be detected by selecting the third oscillation.
The common covering of some gear tooth cause of the jaws can be compensated by interpolation. The reached standard deviations for the detection of eccentricity depend on the number of measurements taken. In the common configuration (3000 Points per gearwheel at 3000 Hz measurement frequency and 50 rpm, extraction of the root circle) the standard deviation is about 0.5 µm (0.020 thou).
Beside the spectral analytic data processing, established information, for example the pitch, can be obtained from the measured data. A master gearwheel (involute gear system, modul: 2 mm (0.079 in), number of teeth: 30, pressure angle: 20°, helix angle: 20°) was manufactured by Frenco GmbH, Germany, including specified pitch errors of 25 – 150 µm (0.98 – 5.91 thou) on six consecutive teeth. The obtained values of the tooth thickness are shown in figure 7.

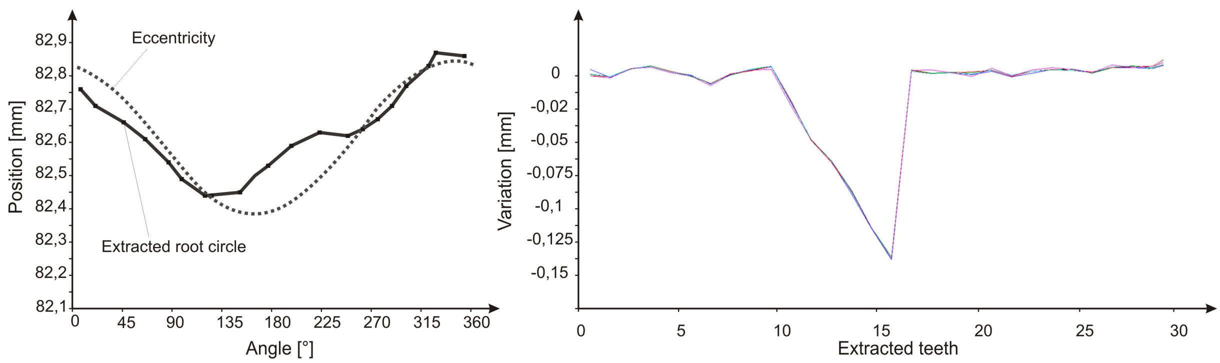

Figure 7: Detection of eccentricity and results of tooth thickness processing

Most important limitations concerning the possible accuracy are the resolution of the rotary encoder and the reference diameter of the gearwheel. In addition to that, the optical cooperativity and the number of measurement points per gearwheel are important.
The achieved reproducibility for the tooth thickness is about 0.8 µm (0.031 thou) for the master gearwheel and about 1.6 µm (0.063 thou) for the camshaft gearwheel.
The individual thickness of the tooth can be also used for an allowance oriented correction of eccentricity.

The accessible cycle times strictly depend on the number of measurement points per revolution. In the test setup 3000 points per gearwheel have been taken. At a measurement frequency of 3000 Hz and 50 rpm a measurement including preprocessing takes 1.9 seconds. Including saving data and postprocessing the cycle times are about 2.5 seconds.
Using the new 15.000 Hz Version of the ConoProbe, a measurement up to 1800 points per gearwheel is possible during the acceleration phase of the lathe. The whole measurement process including saving takes not a second. At the moment, signal quality and reproducibility of the fast measurement can not reach the 3000 Hz values.

Next step is the utilization of the extracted information. There are three possibilities: First, the gearwheel is distorted or has significant defects and will not further be manufactured;

second, the gearwheel shows an eccentricity due to the clamping and third, the gearwheel is ready for the following manufacturing steps.
The first possibility is interesting for quality assurance and quality management, the third possibility needs no notification to external customers. The second one can be corrected by eliminating the eccentricity. Depending of the manufacturing process, there are two different methods.
In the CRC 489 a mechatronic chuck was researched. This chuck has four integrated piezoelectric actuators, which can be used to compensate an eccentricity. In each direction, two actuators are placed in opponent-arrangement and can move the clamping system. This structure allows a positioning of the workpieces in two degrees of freedom. The actuators offer a high stiffness to ensure a high precision turning process and an achievable compensation range of about 100 µm (3.934 thou) in each direction [2].

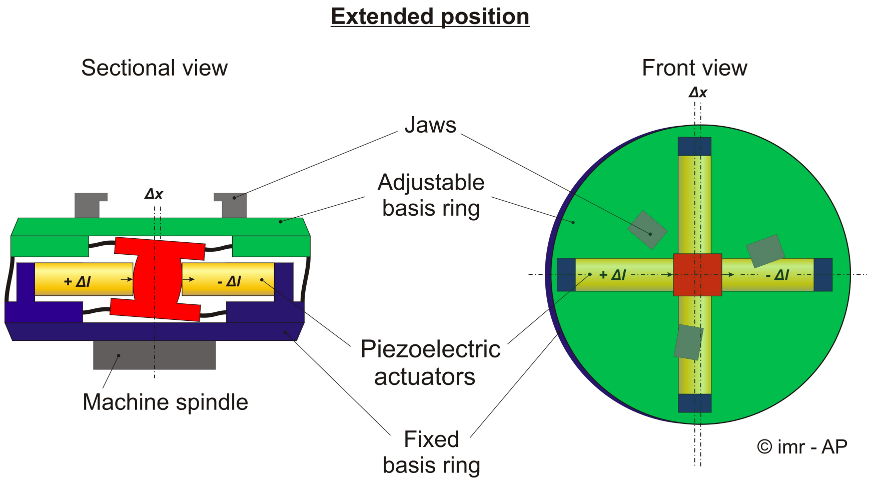

Figure 8: Principle of the mechatronic chuck [2]

The alternative way is the use of machine's degree of freedom combined with driven tools. In this case the turning process must be converted into a milling process. The gearwheel is fixed in a known position and the milling cutter corrects the eccentricity and manufactures the central bore. In machines with one directional radial feed, the angle of the ideal position must be in the direction of the radial feed for the described compensation.

Concluding Remarks and Perspectives

This paper shows a fast method for the in-line quality assurance of gear wheels. Using an optical distance sensor based on the conoscopic holography, the geometry of a gearwheel can be captured in one transverse plane. Eccentricity, distortion and clamping error due to the chucking power can be detected. Including a counter card, pitch and allowance variations can be detected and used to correct eccentricity or for process regulations.
The achievable accuracy depends on the resolution of the rotary encoder, amount of measured points, optical cooperativity and geometry of the gearwheel. In the shown test setup, reproducibilites << 1 µm (0,039 thou) at cycle times about 2.5 seconds can be reached.
Next steps are automated endurance tests in a lathe using the protection cover (shutter), industrial PC and Profibus communication between the industrial PC and the machine tool controller. Further more, intensive tests with the 15000 Hz Version of the laser sensor are planed in order to increase accuracy and get reliable measurements in the acceleration phase of the lathe.

Acknowledgement

The authors would like to thank the German Research Foundation (DFG) for their support and funding of the presented research project and the CRC 489.

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