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Optical multi-distance measurements of spur gears

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Summary:

Standard gear measuring systems (e. g. coordinate measuring machines) are conditionally suitable for extensive large gear measurements due to individually limited measuring volumes. Therefore, an optical scalable multi-distance sensor system consisting of a confocal chromatic sensor in combination with a rotary table is presented and referenced with a tactile measurement. The determined standard deviation of the profile slope deviation of a small spur gear amounts 1.23 µm. Further, with a suitable calibration strategy, simulations show that uncertainties of less than 1 µm can be achieved.

Keywords: large gear, optical measurement, confocal chromatic sensor, multi-distance measurement, model-based evaluation

Introduction

In dimensional metrology, measurements of large gears are challenging due to high claims on tolerances of single-digit µm [1]. With regard to the manufacturing process of large gears, the standard gear inspection with a random test scope of four teeth is not sufficient. Compared to small gears, asymmetrical heat input and tool wear occur due to the larger chip volume and the longer machining time [2]. Standard gear measuring methods, such as coordinate and gear measuring machines, are only conditionally suitable for extensive large gear measurements due to the fixed measuring volume [3]. Scalable gear measuring approaches are desirable to detect deviation parameters of large gears with 1 µm uncertainty. Recently, optical sensor systems have been investigated for extensive gear measurements. Optical gear measurement approaches based on the triangulation principle are presented in [4, 5]. Guo et al. achieved measurement uncertainties of the profile deviation of the teeth of 1 µm. They used a laser line triangulation sensor in combination with a rotary table. In 2019, Chen et al. investigated an optical gear measurement approach by using moiré projection [6]. The estimated mean measurement uncertainty for the profile deviation is 2.67 µm. In summary, the current state of research shows the potential for optical gear measurement concepts. However, no measurement approach mentions the applicability for large gears. As solution, an optical scalable multi-distance measurement approach for large gear measurements consisting of a confocal chromatic sensor in combination with a rotary table is presented. Initially, the applicability of the measurement concept is investigated on a small spur gear due to a simpler handling. As fundamental shape parameter the profile slope deviation is to be determined with a desired uncertainty of 1 µm.

Measurement principle

In this article, the profile slope deviation is evaluated for a small spur gear. The profile slope deviation $f_{H\alpha}$ is defined as the deviation of the actual slope from the nominal slope of an involute. The profile slope deviation is determined by a linear regression into the plumb line distances d_{plu} between actual and nominal geometry of the tooth in a defined evaluation range. According to [7], the points P_a of the actual geometry of a tooth flank can be described as function of the points P of the nominal geometry of an involute spur gear and the plumb line distance d_{plu}. To quantify the plumb line distances and thus the profile slope deviation, the inverse problem $d_{plu}(P, P_a)$ must be solved. Therefore, the actual profile geometry of the tooth flank must be measured. Fig. 1 illustrates the optical multi-distance measurement concept. A confocal chromatic distance sensor is aligned vertically to the teeth in the transverse section of the spur gear and continuously measures the distance to the teeth surface while rotating the gear. By calibrating the sensor system in position and alignment, the distance information is transformed into coordinates in a measurement coordinate system (x, y). With a model-based evaluation according to [7], the plumb line distances and thus the profile slope deviation of individual teeth can be calculated.

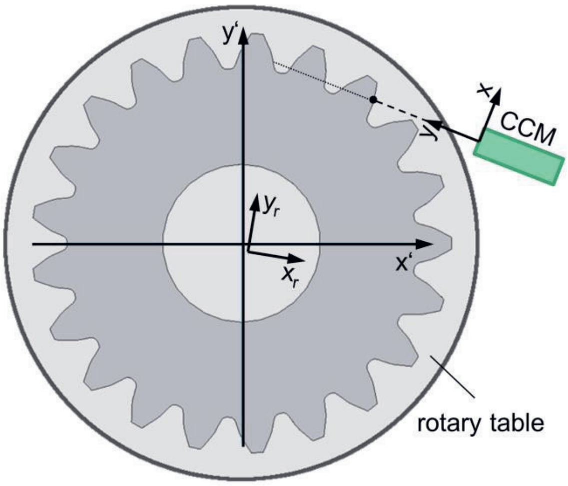

Fig. 1. Measurement principle consisting of a confocal chromatic (CCM) sensor (x, y) in combination with a rotary table (x_r, y_r) measuring the distance to the teeth flanks (x', y') depending on the rotation angle.

Results

In order to proof the applicability of the optical gear measurement system, measurements on a small involute gear with a normal module m_n = 3.75 mm and 26 teeth are performed. With a subsequent model-based evaluation, the profile slope deviations of the teeth are determined. The results are referenced with a coordinate measuring machine. Fig. 2 shows the optically detected profile slope deviations and reference values for four random teeth with the single standard deviation for an accessible evaluation range of one third of the tooth height at the tip.

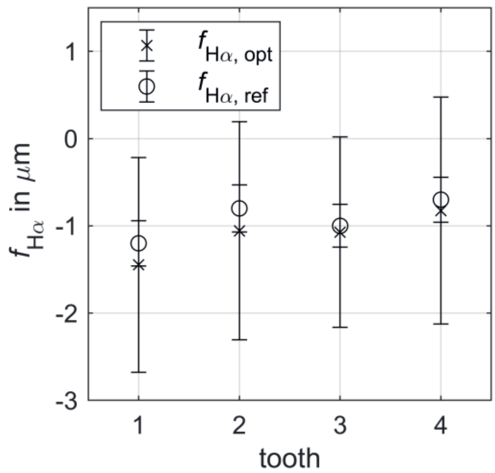

Fig. 2. Profile slope deviation of four random teeth with the single standard deviation. Measured with the optical sensor system $f_{H\alpha,opt}$ and referenced with a coordinate measuring machine $f_{H\alpha,ref}$.

As a result, the optically determined and the reference values of the profile slope deviation are in agreement within the calculated random errors for k = 1. While the random error of the reference measurement amounts 0.26 µm on average, the random errors of the optical values are 6 times higher and amount 1.23 µm on average for k = 1. The aimed uncertainty of 1 µm is therefore narrowly missed by 0.23 µm. A general applicability of the sensor concept is nevertheless shown. Main contributions to the random errors are the position and alignment uncertainties due to the sensor calibration. In the future, a suitable sensor calibration strategy must be implemented, in order to reduce the total measurement uncertainty. With a suitable calibration strategy, simulation results show that uncertainties of less than 1 µm can be achieved. Hence, a proof of principle of the optical multi-distance gear measurement approach was obtained.

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