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# Gear measurements using optical point autofocus profiling

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**Abstract**
Traditional methods for gear inspection, as specified in ISO 1328-1, involve measurement of profiles on a flank to determine helix deviation and profile deviation. For such measurements, it is common to inspecting only a selected number of teeth and only a small number of profiles are measured per flank. Although such methods are efficient for tolerance evaluation, they do not obtain surface topography information on gear flanks, which can be critical in tribology studies. Furthermore, due to the determined flank geometry may vary depending on the location of the profiles being measured, and hence may not be representative of the entire gear. In this work we propose the optical measurement of gear flanks using a point autofocus instrument. Measurement of the flank surface on every tooth of the gear is performed to obtain both form and surface topography information. This study describes profile measurement and 3D complete gear measurement, and compares obtained point cloud data with the nominal CAD model.

Keywords: point autofocus instrument, non-contact, gear measurement, form and surface topography measurement

## 1.Introduction

It is common to use contact stylus measuring instruments for tooth flank form measurements, however, miniaturisation and high precision parts demand non-contact measuring instruments. Moreover, the demand for measuring soft and delicate materials, such as polymers, with non-contact measuring instruments has been increasing. Several optical instruments have been developed to measure gears. Takeoka et al developed a laser interferometer system to measure the profile form deviation of an involute artefact [1]. Lu et al proposed an optical method of gear flank measurement based on the principle of phase shift optical triangulation [2], in which the surface topography at micrometre level resolution was obtained by a phase unwrapping algorithm. However, the system by Lu et al. did not provide any characteristic parameters used in the gear industry. Fang et al. developed a laser interferometric system to measure the flank surface of a spur gear and a helical gear [3].

In this work, a non-contact point autofocus instrument (PAI) was used to perform form measurements of a helical gear. Geometrical deviations in the gear profile (total, form and slope deviations) were determined according to the specifications in ISO 1328-1 [4]. Gears are widely used for power transmission, and require precision in order to achieve high transmission efficiency [5]. It is essential that gear geometry conforms to the design specifications, as gear geometry deviations influence power transmission, fatigue life and noise [6]. After a gear is designed and manufactured, it is essential to measure and evaluate its geometrical dimensions [7]. Evaluation of the geometrical specifications of cylindrical gears is specified in ISO 1328 [4]. Measurements of gear geometry are traditionally performed using specialised contact instruments, such as gear measuring instruments and coordinate measuring machines (CMMs) [8]. Traditional gear inspection typically only comprises one profile and one lead line on both flanks of four [5]. With the PAI, the entire gear surface was measured with dense sampling, producing approximately 15 000 points per tooth. The measured tooth geometry with the PAI was then compared with that obtained using a precision CMM.

## 2. Measuring instrument

Gear measurements were carried out with a PAI using an objective lens with 50× magnification and numerical aperture of 0.5. The instrument measures the surface by automatically focusing a laser beam at a point on the specimen surface, moving the specimen surface in a fixed measurement pitch using an *x*-*y* scanning stage, and measuring the specimen surface height at each focused point (see [9] for a detailed description of the PAI). The instrument operates in a similar manner to a CMM, where the physical stylus is replaced by a laser beam with approximately 1.5 µm spot size.

### *2.1 Profile measurement*

Figure 1 shows the PAI measuring one tooth of the gear (module = 1, spiral angle = 21°30′ right). Four flank profiles of the gear teeth were measured with a dedicated gear measurement module included in the instrument software, which deploys a strategy of positioning the gear in favourable positions, where both the left and right flanks of each tooth are accessible [10].

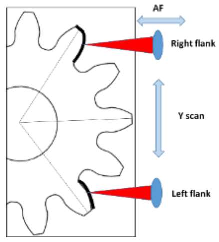


**Figure 1.** Gear profile measurement strategy

The right (R) and left (L) flanks (see Figure 1) are measured separately at positions where the surface slope is well within the maximum acceptable local slope angle of the instrument, in order to improve the accuracy of profile measurement. This strategy overcomes the common difficulties in optical instruments to measure surfaces with very steep slope angles. The point autofocus probe has high angle tracking capability.

## 3.Results

### *3.1 Measurement system analysis*

A gauge repeatability and reproducibility (GR&R) test was performed to analyse the measurement performance of the PAI regarding two gear parameters on four gear teeth, as shown in Table 1. Repeatability is determined using five repeated measurements with identical settings. Reproducibility is determined using different stepping pitches of 10 µm and 5 µm.

**Table 1.** Measurement system analysis (GR&R)

| Gear parameters | repeatability variation % | reproducibility variation % | total Gauge (R&R) |
|---|---|---|---|
| Fα | 8.19 | 2.29 | 8.50 |
| $F_P$ | 2.47 | 1.12 | 2.71 |

The total variations for total profile deviation *Fα* and cumulative pitch error $F_P$ are less than 10% and the system should be satisfactory for repeatability and reproducibility performance.

### *3.2 Point cloud data colour map*

It is important to define the error in gear geometry during gear manufacturing. Gear flanks analysis can be used to identify the causes of error. The PAI was used to measure the entire helical gear, where one hundred profiles were measured along a 6 mm tooth width with 10 µm step distance pitch. The point cloud obtained by the PAI was aligned with the nominal CAD model in Polyworks software. The CAD model was created with Solidworks based on nominal specifications. Fifty iterations were carried out to meet the maximum convergence distance between the point cloud of the measured gear flanks with the CAD model. A colour map was used to determine the deviation of the point cloud from the CAD model (see Figure 2).

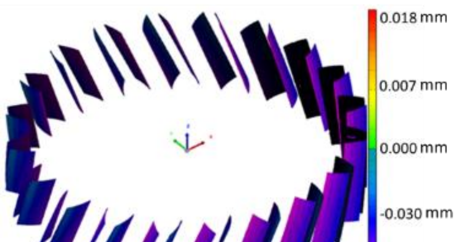


**Figure 2.** Colour map for the helical gear

The deviation between the CAD model and the ground surface varied between 0.018 mm and -0.060 mm. Further work is needed to investigate the causes of error in the manufacturing process.

### *3.3 3D point cloud comparison*

One tooth of the helical gear was measured by the PAI and a Zeiss F25 precision CMM to obtain 3D point clouds. Multiple profiles along the circumference of the gear were measured. The point clouds obtained from these two instruments were different in the distance between profiles, number of profiles measured and the pitch step distance (see Figure 3).

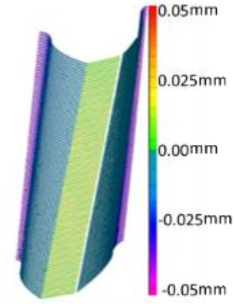


**Figure 3.** PAI point cloud comparison

These two point clouds are difficult to compare directly; for this reason, the point clouds were aligned with the CAD model using Polyworks software. The standard deviations of the distances from the points in each point cloud to the nominal CAD surface are shown in Table 2.

**Table 2.** Compare CAD model to point cloud

| Instrument | PAI \|nominal CAD | CMM \| nominal CAD |
|---|---|---|
| Number of points | 14958 | 1295 |
| Std Dev/µm | 0.086 | 0.106 |

## 4. Conclusions

In this paper, PAI and a precision CMM were used to perform 3D measurements of one gear tooth and the deviations of the measured point clouds from the nominal geometry were compared. The different standard deviations for the two instruments may be caused by alignment error between the point cloud and CAD model or by tilt adjustment of the gear mounting in PAI. It has been shown that the PAI has the capability, not only to measure gears according to the ISO standard, but also to measure 3D gear form. Traditional gear measurement methods based on profile, lead and pitch measurements at predefined flank lines can only give limited information about the gear. 3D measurements have the capability to define measuring points on the complete gear flank and obtain more gear geometry details beyond what is specified in gear standards.

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