Making use of phase-contrast in dimensional µCT-measurements of weakly absorbing objects

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Abstract
The effects of refraction (phase-contrast) are normally considered as disturbances in high-resolution µCT-measurements. We show that in the case of small objects with low absorption a single-distance phase-retrieval algorithm not only reduces the edge enhancement, but also raises the signal-to-noise ratio sufficiently to allow dimensional measurements. This is exemplified at an optical element for optical fibre connectors.

1 Introduction
Standard µCT makes use of X-ray attenuation. Going to resolutions smaller than a few micrometers and acceleration voltages below 100 keV, the effects of refraction (also referred to as phase-contrast or small-angle X-ray scattering) can be measured. If standard reconstruction methods are used without special pre-filtering algorithms, they lead to artefacts. If the X-ray attenuation of the object is sufficient, the refraction signal is normally considered as disturbing and will be removed, see e.g. [1] and [2]. In the case of composites with materials of similar attenuation it may be used to distinguish the constituents, see e.g. [3].
Dimensional µCT measurements of small plastic parts, e.g. for precision-moulded low-cost optical interconnects in consumer applications [4], are difficult, because of their low attenuation. Even going to low acceleration voltages (<60 keV) doesn’t result in a sufficient absorption contrast. The large distance (~1 m) between object and detector, required for the high spatial resolution, leads to a pronounced edge-enhancement due to X-ray refraction.
Using a single-distance phase-correction algorithm – despite the violation of some of its assumptions – the filtering creates data-sets with sufficient signal-to-noise ratio for dimensional measurements.
With the phase-contrast filtering applied, the CT-measurement can be used for quality control of precision-moulded low-cost optical interconnects.

2 The measurement object
Optical interconnects are beginning to see greater market penetration in high-performance consumer electronics [4]. They are used for high bandwidth data transmission where conventional electrical cables are limited by frequency dependent signal attenuation and thus very short lengths. Consumer applications require very low system cost. Inexpensive optical components, such as injection-moulded plastic lenses in combination with an adapted optical fibre design have to be used [5]. Reproducibility of the moulded parts is crucial since the optical components need to be assembled passively, i.e. without powering the system, to allow for low-cost high-volume manufacturing.
The measured “photonic turn” element (Fig. 1) is made of a polymer material by injection moulding. It has multiple optical elements, whose position and alignment are crucial for the function: notches for holding the optical fibres, a tilted plane serving as a mirror by total internal reflection, and aspherical lenses for adapting the beam widths from the Vertical Cavity Surface-Emitting Laser (VCSEL) to the optical fibres and from the optical fibres to the photodiode.

3 The measurement task

The measurement task is to determine the positions and the alignment of the notches, the mirror-plane, and the lenses relative to each other and to the connector housing, when assembled. Because some functional elements are on opposite sides of the object, a three-dimensional measurement of the geometry is needed.

Micro-CT provides the capability to measure in three dimensions with a resolution of $\leq 5 \, \mu m$. The shape of the object can thus be measured with a sufficiently high accuracy. Measurements of the lenses with higher resolution, obtained by an optical confocal microscope, can be aligned onto the CT data-set, so that the exact optical path can be calculated from the surface data and the material properties.

4 Micro-CT measurements

$\mu$CT measurements were performed on the BAM 225kV-$\mu$CT-device. This device features an X-RAY WorX micro-focus X-ray tube with 225 kV acceleration voltage and a focal spot size of approximately 5 $\mu m$. The detector is a flat-panel from PerkinElmer with 2048x2048 pixels at a pitch of 0.2 mm. The measurement parameters were: 60 kV acceleration voltage, 120 $\mu$A current, 3.3 $\mu$m voxel size, 10 s exposure time per projection.

The object has very low absorption also for low-energy X-ray photons (see Fig. 2). The transmission in the direction of maximum attenuation is still at 84 %. Even at 60 keV acceleration voltage, most of the photons have energies below 20 keV (see Fig. 3), so, lowering the voltage to 40 keV (the minimum for this tube) wouldn’t improve the absorption contrast significantly.
When reconstructing the data set without further processing (Fig. 4), it becomes obvious that the data is strongly affected by X-ray refraction, as can be seen by the overshoot at the object’s edges, in both, the reconstructed data and already in the projections (Fig. 2).

The refraction effects (also known as “phase contrast”) are normally negligible in industrial µCT measurements, but are reported in synchrotron measurements, due to the small pixel-sizes and low X-ray energies used there.
In the case reported here, refraction becomes visible due to the combination of a low X-ray energy (<20 keV) and a large distance between object and detector (~1 m), which lead to a deflection at the site of the detector of ≥1 pixel-pitch. For this object, the refraction makes it difficult to extract the surface, because artefacts arising from the edge-enhancement reach similar gray-values as those of the material, and, additionally, the gray-values of the material in the histogram are not clearly distinguishable from those of the surrounding air due to the low signal-to-noise ratio.

5 Data processing

Different approaches exist to use the additional information from the refraction signal or to remove its signal from absorption data. The best way is to use the additional information without loss of spatial resolution by performing holography [6]. CT-measurements are performed at different object-detector distances to accurately determine the phase-signal. For this approach parallel monochromatic radiation is needed, which is available only at synchrotron sources. This method can, thus, not be used with µCT data.

For single-distance phase-correction algorithms two approaches are possible: correction already in the projection images (see e.g. [7] and [8]), or correction of the reconstructed volume [1], when the projection data is not accessible. Although they make certain assumptions, e.g. monochromatic radiation, parallel beam (i.e. no differences in magnification for different regions of the object in cone-beam geometry), low absorption, even with strong deviations from them or otherwise uncertain parameters, an enhanced data quality can be achieved (see e.g. [7] and [8]). Application of the filters reduces both, the spatial resolution but also the noise in the data.

The filtering was performed with the software ANKAphase [9], which uses an algorithm described by Paganin et al. [10]. The parameters for beta, delta, distance and energy were chosen arbitrarily (they are not independent, but linearly coupled) in such a way that the edge enhancement was reduced as far as possible while limiting the blurring. Figure 5 shows a slice through the reconstructed volume.

As can be seen, the edge enhancement has nearly vanished. Along the longest edges edge-artefacts are prominent. The edges are smoothed to a certain extent, resulting in an effective spatial resolution of ~15 µm (65 lp/mm at 20% of the MTF, determined with the ImageJ-plugin “Slanted Edge MTF” [11]), but the shape can still be determined with high accuracy.
6 Results
The further analysis has been performed using VGStudio MAX 2.2 (Volume Graphics GmbH, Heidelberg, Germany). After applying the adaptive surface determination algorithm, dimensional measurements were performed, like measuring the positions and orientations of the optical elements by fitting regular geometries (see Fig. 6). The surface also was exported as STL file for further analysis.

Figure 6: The object surface with fitted reference objects: cylinders at the optical fibres, a plane at the mirror surface, and circles at the positions of the lenses. The projections of the optical axes of the fibres onto the reflective plane are marked by crosses.

With that information the mould cavities and the moulding process parameters can be controlled and adapted if needed.

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