euspen's 26th International Conference & Exhibition, Krakow, PL, June 2026
www.euspen.eu

Systematic error correction for thickness measurements with optical distance sensors

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Abstract

Confocal chromatic optical distance sensors enable rapid, non-contact thickness measurements of transparent materials. This technology is particularly promising for applications in which the inner surface of components made of translucent glass or polymer is not accessible. The refractive index of the transparent material is an important input quantity and can be the dominant error source. This work proposes an opto-tactile error correction approach, implemented on a multi-sensor coordinate measuring machine, in which both confocal chromatic and contact probing measurement points are acquired. Two glass carpules and two glass syringes were measured using repeated acquisitions across multiple axial sections, collecting paired inner/outer surface data to compute thickness. A correction factor is identified via least-squares minimization to best match confocal and contact-derived thickness values; the resulting factor is then used to scale optical measurements. Preliminary results show that unknown materials exhibit a larger, yet repeatable, mismatch. The proposed correction reduces the systematic error in thickness measurements and yields an accurate estimate for the specific measurement condition, thereby supporting optical thickness inspection of transparent components.

Thickness Measurement; Confocal Chromatic Sensor; Optical Probe; Error Correction

1. Introduction

Confocal chromatic distance sensors have seen increased adoption as non-contact probes for dimensional metrology. Interestingly, the chromatic aberration principle enables measuring thicknesses for transparent materials by detecting the two wavelengths having maximum intensity, in focus on the two surfaces of the part [1] (Figure 1).

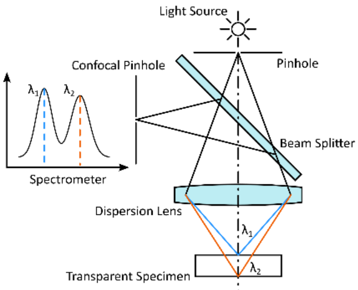

Figure 1. Thickness measurement with a confocal chromatic probe.

Representative applications of optical thickness measurements include automotive glass and polymeric parts (e.g. windshields, lighting covers, etc.), glass tube production, liquid crystal display adhesives and optical lenses [2].

Accurate thickness evaluation with confocal chromatic probes requires knowledge of the refractive index of the workpiece material, to account for light refraction [3]. The basic formula used to account for optical properties is:

$$d = \frac{d'n'}{n} \tag{1}$$

where d is the measured material thickness, taking into account the optical properties; d' is the material thickness obtained by the confocal chromatic probe, without considering the material influence; n is the refractive index outside of the material (typically air); n' is the specimen material refractive index.

In typical industrial conditions, however, the refractive index of the specific transparent materials is unknown, and a generic value n_s is used. This leads to inaccuracies in measurements, and an error e is introduced:

$$e = \frac{d'(n' - n_s)}{n} \tag{2}$$

This error can be considered systematic for a given material and measurement configuration and can therefore be corrected. The present work investigates a correction approach using a multi-sensor coordinate measuring machine (CMM) to acquire both contact reference data and confocal chromatic measurements.

2. Methodology

The experimental part of this research comprises a series of thickness measurements performed on different glass products. Specifically, two syringes and two carpules (i.e., pharmaceutical cartridges with a puncturable cap).

All samples are measured using both tactile probing and the confocal chromatic probe, both mounted in a Zeiss O-Inspect 3-2-2 multi-sensor CMM, which has MPE figures for 3D length measurements of 2.4 µm + L/150 for contact probing and 3.2 µm + L/150 for confocal chromatic probing. Each container is placed in the measuring volume using Mitutoyo "eco-fix" fixtures, oriented with its axis along the CMM x-axis.

Alignment is performed by fitting the outer cylindrical surface of the container to define an axis, and by setting the origin at the intersection between this axis and the plane fitted to the syringe flange or the carpule cap. Contact measurements are performed with both vertical and horizontal styli to access both the outer and inner surfaces. The acquired data consists of a series of points at multiple axial positions (Figure 2), enabling both contact and confocal-based thickness evaluations at several cross sections of the container.

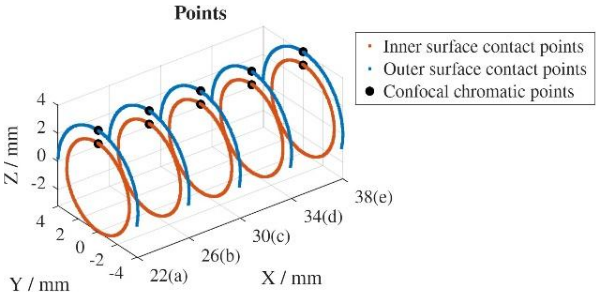

Figure 2. Data acquired on the glass container geometry.

Three measurement cycles are repeated for each sample, highlighting two different conditions: for the carpules, made of known material (fused silica), the opto-tactile thickness difference is limited to at most 10 µm; in contrast, for the syringes, whose material is unknown, the observed difference is significant, on the order of a tenth of a millimetre.

2.1 Correction factor

The opto-tactile difference observed is considered a systematic effect caused by using approximate refractive indexes. A correction factor c_f is defined as a scale factor that best matches the optical thickness values to the contact reference values, utilizing a least-squares approach:

$$c_f = \arg\min_c \left\| t_{cont} - c t_{conf} \right\|^2 \quad (3)$$

where t_{cont} is the vector of thickness values acquired by contact probing at different locations along the container axis, and t_{conf} represents a vector of thickness values acquired by the confocal chromatic probe at the corresponding locations. With the correction factor applied, the measured material thickness expressed in equation (1) becomes:

$$d_{corrected} = c_f d = c_f \frac{d'n'}{n} = \frac{d'(n'c_f)}{n} \quad (4)$$

Accordingly, $n'c_f$ can be interpreted as an estimate of the unknown refractive index for the specific measurement condition, based on contact and chromatic confocal data.

3. Results

Table 1 gives an overview of the differences between carpules and syringes, showing that the confocal chromatic principle is accurate when the material is known. The average results of three measurement cycles per each specimen are shown; each cycle considers multiple sections.

Table 1. Mean thickness **(d)** and standard deviation **(std)** figures

	Carpule 1	Carpule 2	Syringe 1	Syringe 2
$d_{contact}$/mm	0.9515	0.9579	0.9080	0.8954
$std_{contact}$/mm	0.0016	0.0044	0.0010	0.0026
$d_{confocal}$/mm	0.9607	0.9550	0.9327	0.9166
$std_{confocal}$/mm	0.0007	0.0031	0.0010	0.0023

As expected, confocal chromatic thickness measurements are most accurate for the two fused silica carpules, which have a known refractive index. The proposed approach for systematic error correction shows accurate results that are consistent with the reference data provided by contact probing.

The correction factor c_f is calculated for both syringes; to prevent self-correction, the factor obtained from one syringe is used to correct the results of the other. The results in Table 2 show that this approach returns corrected thickness values that are consistent with the contact measured ones.

Table 2. Cross-applied correction factors **(c_f)** on syringes

	Syringe 1	Syringe 2
$d_{contact}$ /mm	0.9080	0.8954
$d_{confocal}$ /mm	0.9327	0.9166
c_f	0.9735	0.9768
$d_{corrected}$ /mm	0.9111	0.8923
$d_{contact}$-$d_{corrected}$ /mm	-0.0031	0.0031

The same approach is tested on the carpules, intentionally selecting an incorrect material (e.g., D236T glass) and performing the correction. Table 3 shows promising results and agreement between the uncorrected results with the correct fused silica setting and the corrected results obtained using the incorrect D236T material setting.

Table 3. Carpules: correcting D236T glass measurements

	Carpule 1	Carpule 2
$d_{contact}$/mm	0.9515	0.9579
$d_{confocal\_FS}$/mm	0.9607	0.9550
$d_{confocal\_D236T}$/mm	1.0016	0.9996
c_f	0.9502	0.9584
$d_{corrected}$/mm	0.9599	0.9499
$d_{contact}$-$d_{corrected}$/mm	-0.0084	0.0080
$n'c_f$	1.4473	1.4597

Moreover, the $n'c_f$ estimate of the refractive index starting from the D236T refractive index of 1.5231 returns values close to the correct refractive index of the fused silica glass, 1.4585.

4. Conclusions and future work

This work presents an effective error correction approach for thickness measurements with optical distance sensors in dimensional metrology. The approach consists in the correction of the refractive index influence by applying a correction factor, calculated from contact reference data. Experimental results show that the corrected opto-tactile difference is reduced to at most a few micrometres.

Applying a correction factor identified on one specimen to another specimen indicates that the method has potential for batch inspections, provided stable measurement conditions. This is particularly interesting for large production lots, where the opportunity to measure one sample contact-wise and correct all the other optical measurements can enable fast and accurate in-line inspection.

Future work will include the identification of an uncertainty contribution for the error correction and more extensive tests on larger sample sets.

Acknowledgements

The project (23IND08 DI-Vision) has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States. The authors would like to thank Brevetti CEA, involved in the definition of the case study.

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