Enhance resolution on OCT profilometry measurements using harmonic artifacts

Marcus Paulo Raele, Lucas Ramos De Pretto and Anderson Zanardi de Freitas[a]

[a]Nuclear and Energy Research Institute, IPEN-CNEN/SP, Av. Prof. Lineu Prestes, 2242, São Paulo, SP, CEP 05508-900, Brazil

ABSTRACT

Optical Coherence Tomography (OCT) systems, as all low coherence interferometry equipments, are mainly grouped in two categories: Time Domain and Frequency Domain, depending on the methodology of data analysis. When measuring samples with high reflectivity, using Frequency Domain systems, detrimental features on OCT images can appear as a replication of a feature at multiple depths on the resulting image, referred as harmonics by the community. This work presents the potential to access better axial resolution and accuracy results on profile measurements analyzing higher harmonics. A variety of measurements of samples with different features, such as roughness, angles and movement evaluation were performed in order to demonstrate the advantages of this approach as a low cost way to have better visualization of reliefs close to the system nominal axial resolution.

Keywords: **Keywords:** optical coherence tomography, harmonics, resolution, Fourier

1. INTRODUCTION

The measurement of profiles, or simply profilometry, is crucial in many fields of knowledge aiming surface inspection, quality control and evaluation. There are several approaches able to provide this information. Some of the most broadly used systems are based on interferometry, cantilevers, confocal microscopy and scanning electron microscopy.

White light interferometry[1], technique based on Low Coherence Interferometry (LCI), is widely considered the gold standard when looking to profilometry, due to its high precision and contactless measurements. Optical Coherence Tomography (OCT)[2], also LCI based, is already available in many laboratories around the world. However, being a system optimized to perform tomographic images of biological samples, OCT does not perform profilometry as good as other white light systems. Nevertheless, it can still perform satisfactory profile measurements for specific cases, as described in the past[3].

It has been reported that when measuring samples with high reflectivity using OCT frequency domain systems[4] a detrimental feature is observed in the signal[5], appearing as a replication of the original structure in various depths on the resulting image, called harmonics.

A previous effort made by our group has showed the potential to access better axial resolution and accuracy results on profile measurements analyzing higher harmonics present on the processed image (post Fourier transform)[6]. The process can be illustrated, for instance, when measuring the height of a step in a sample, as in Fig. 1, where such a height is close to the nominal system resolution. A saturated measurement provided the harmonics structures presented at Fig. 2, in which is possible to visualize the step height becoming better resolved as the harmonic order increases.

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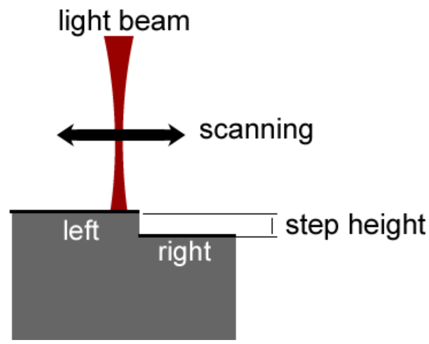

Fig. 1. Illustration of a step height sample hit by a focused light beam. “Left” and “right” as used in equation (2) are defined with respect of the step itself.

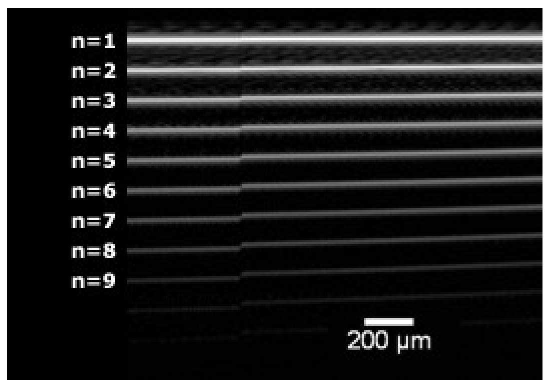

Fig. 2. OCT image of a step height sample. The coherence length of the SLED gives the setup 6 µm axial resolution in air. The sample, in this case, has a 10 µm step. The “n” number indicated the harmonic order.

This harmonic feature obeys a linear and predictable behavior, thus can be summarized as:

$$H_n = nF \tag{1}$$

Where, H_n represents the position of the n^{th} harmonic in relation to the reference mirror position, F is the position in depth of the root peak (n=1) at FFT, and n is the harmonic order, an integer (n >0). Imagining the case where two points of interest have a height difference of dz, this difference is amplified linearly with the harmonic order and, at the *nth* harmonic; the difference dz will be amplified by a factor of n. Taking Fig. 1 notation, the step can be determined as function of the harmonic order:

$$Step = H_{left,n} - H_{right,n} = n(F_{left} - F_{right}) \tag{2}$$

The determination of H_n position is performed directly on the OCT image, through Gaussian fits nearby to the step border or any other feature of interest. One can find that, as the harmonic order increases, more resolved become the feature. More detailed information can be found at the afore mentioned work by our group[6].

In this study a more practical approach was made, evaluating a variety of different features in high reflectivity samples, such as roughness, angles movement, in order to demonstrate the advantages of this approach as a low cost way to achieve better visualization of reliefs below the system axial resolution.

2. EXPERIMENTAL SETUP

For the experiment a Fourier domain based OCT (OCP930SR, Thorlabs, Newton, New Jersey, USA) was used, with axial resolution of 6 µm in air for the SD-OCT system and declared digital resolution of 3.088803 µm.

Different samples were used for three different profile characteristics: A roughness standard (Surfcom, model E-MC-S24B) with a peak to valley distance very close to the system axial resolution; a cutter knife blade (18x100 mm) aiming to demonstrate angle measurements and a spherical mirror to show the application in curvature evaluation, Fig. 3.

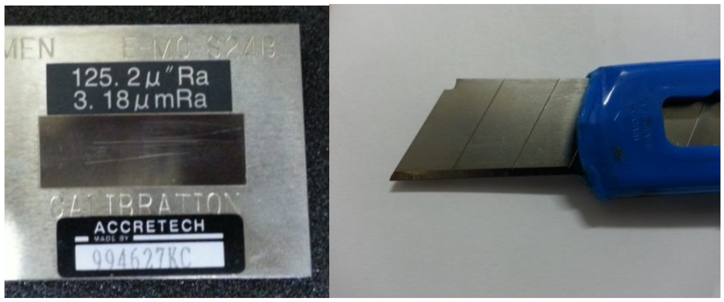

Fig. 3:Sample´s photography: Roughness standard (left); Cutter knife blade (right).

A white light based profilometer (ZeGage, Zygo, Middlefield, CT, USA), with a 20x objective, was used as gold standard for comparative effects, assuming its measurement represents the true value (no error or uncertainties) as its precision and accuracy are far better than OCT, approximately 0.4 µm.

Profilometer measurements aiming characterization of the roughness standard and of the cutter knife blade edge were taken, Fig. 4 and Fig. 5, respectively. The values of interest were measured; the peak to valley height (10.044 µm) and the edge angle (6.02°).

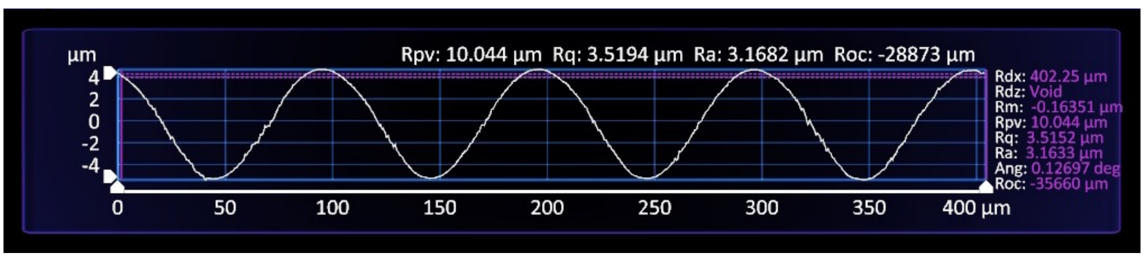

Fig. 4: Profile of the roughness standard measured with white light profilometer. Peak to valley height of 10.044 µm.

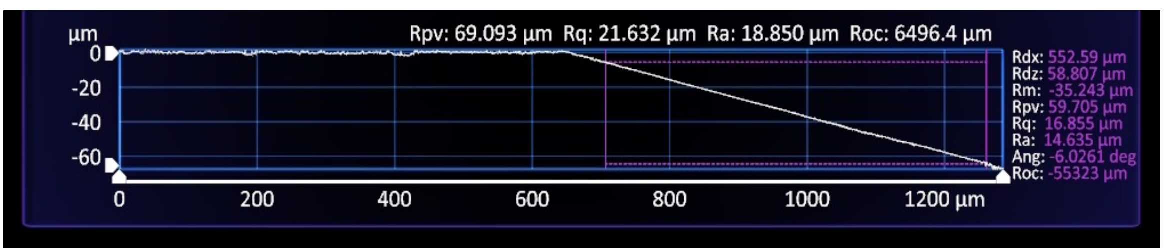

Fig. 5: Profile of the cutter blade edge, measured with white light profilometer. Angle measured of 6.02°.

Studies was also carried on moving samples, the idea was to verify the possibility of access subtle axial movements through the harmonics. For this a function generator (model F62A; Wavetek San Diego, Inc., San Diego, CA, USA) was connected in a loudspeaker, where a mirror was positioned, as illustrated at Fig. 6.

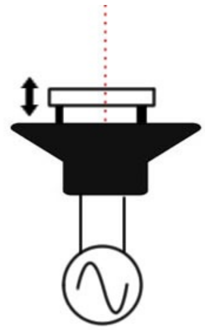

Fig. 6: Loudspeaker and function generator connected. The dotted line represents the OCT laser beam and the arrow indicates the oscillatory movement of the mirror.

3. RESULTS AND DATA ANALYSIS

3.1 Roughness measurement

The roughness measurement was carried with the OCT system in conditions that the harmonics could be easily appreciated (saturated image). Then a single image was recorded and analyzed using the software OriginPro 8.5 (OriginLab, Northampton, MA, USA). The OCT image is presented in Fig. 7 along with the fitted peaks for two regions, plotted as a function of depth. The solid line, overlapping the OCT image, highlights the peak region and its harmonics, as the dotted line does with the valley region. Both profiles are plotted at Fig. 7 right, where is possible to see the distance between peak and valley increase at higher harmonics (difference between solid and dotted curves).

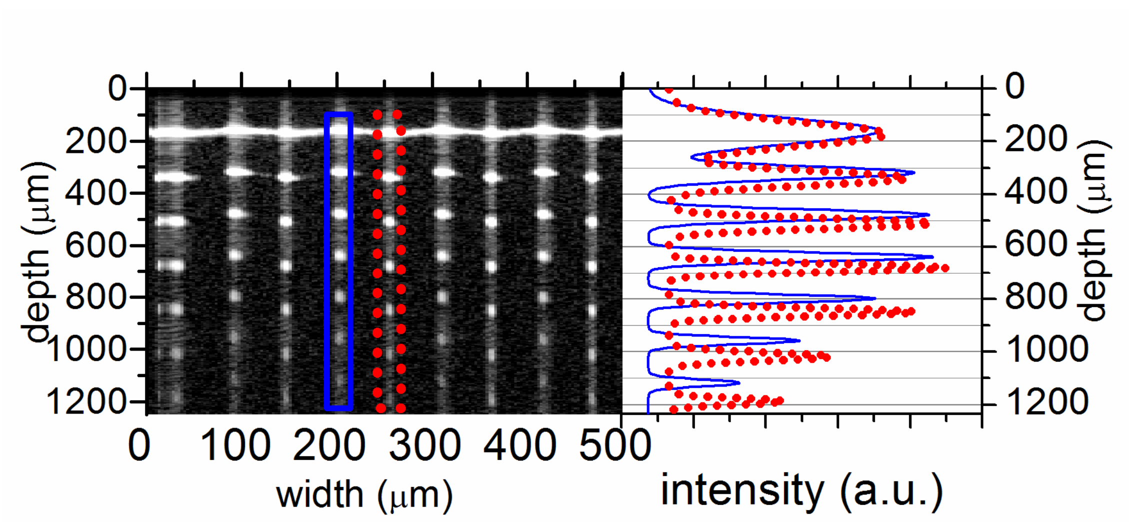

Fig. 7: At right, the OCT image of the roughness standard, with regions of peaks and valley highlighted (solid and dotted lines, respectively). At left the intensity profile, showing the distance between peaks

Over the intensity profiles, Gaussians were fitted, and the results tabulated. It is important to note that the measurements need to be divided by the harmonic order, as equation (1) indicates.

As expected, the first harmonic, gives a broad distribution, partly due to the saturation itself, but as the harmonic order increases the measurement's uncertainty becomes smaller, having the highest precision result in the 5^{th} order.

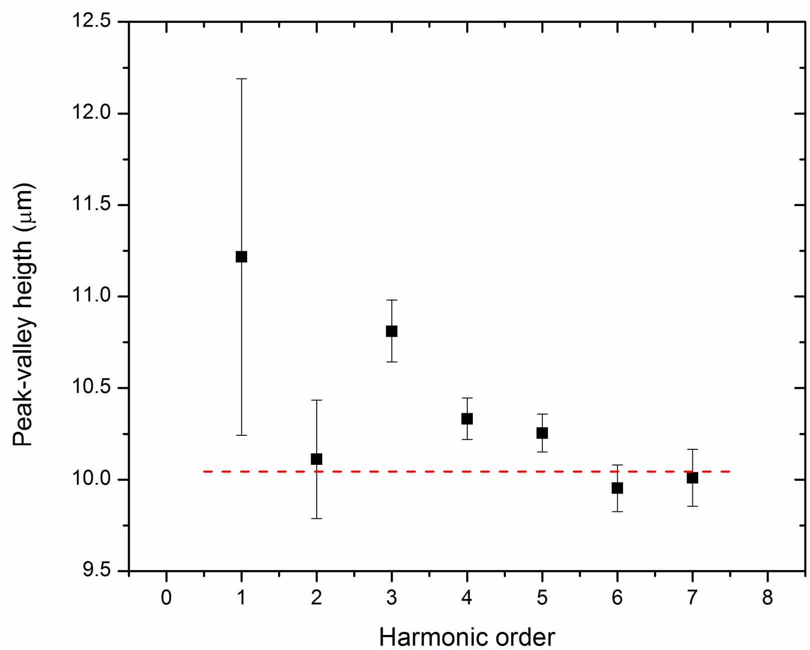

Fig. 8: The peak to valley height as harmonic order function. The dotted line represents the reference value 10.044 μm.

3.2 Angle measurement

To show the advantages of harmonics analysis for angle evaluation, a cutter knife blade was imaged at its edge. The angle could easily be seen in all harmonics with the OCT system, Fig. 10, but in a first visual inspection it is possible to see that at higher harmonics the angle becomes sharper.

To evaluate the angle seven locations in the razor body were taken to set it as the reference surface. Then another seven points were analyzed at the edge. This procedure was repeated in three harmonic orders, then linear fittings were used to reproduce the surfaces. The angle was defined by the difference of inclination between the body and the edge. The values of interest were given as angular coefficient from the fitting process. The angle could be calculated by subtracting the body and the edge values, dividing by the harmonic order and finally converting to degrees, to have a more suitable unit of measurement.

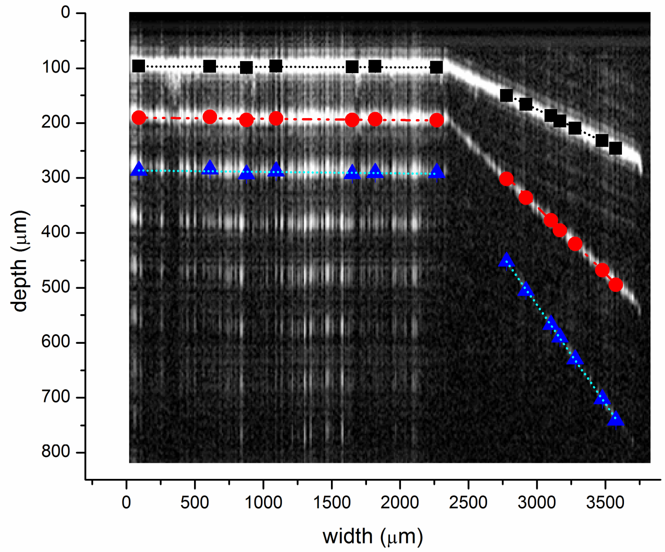

Fig. 9: Cutter knife edge blade OCT image. Three harmonic orders were used to measure the edge angle. The Gaussian curves were used to reproduce the intensity profile and then a linear fit was performed to extract the angle.

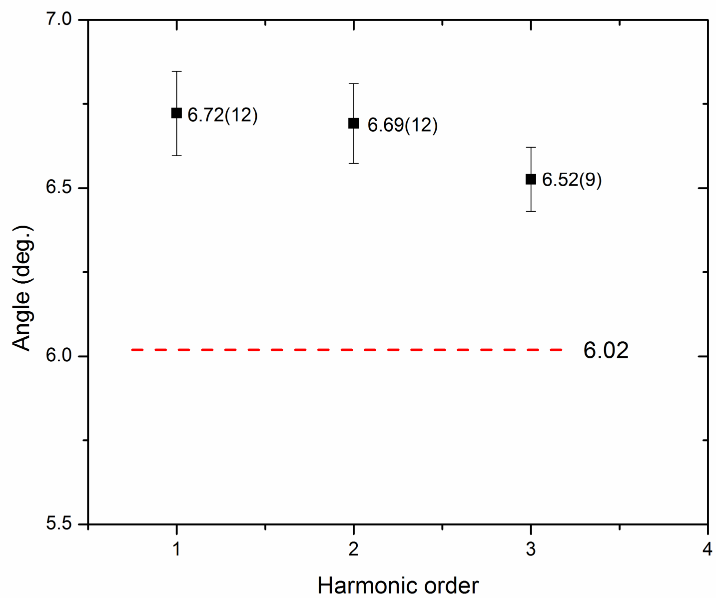

Fig. 10: Measured angle in function of the harmonic order.

At Fig. 10 results are plotted, showing that the reference value (white light interferometry results) was not compatible with OCT results, but for higher harmonics results were closest than in the fundamental, corroborating with the hypothesis of this study.

3.3 Movement

Harmonic analysis are applied mainly for profile measurements, however moving sample also distorts the sample morphology, making possible to verify and even measure subtle movements that are not clear at the fundamental signal. The setup, as previously mentioned, counted with a loudspeaker and a function generator, enabling for adjust the amplitude and frequency of the mirror. To illustrate the potential of this technique, under the same mirror vibration condition 70 Hz, two images were performed: with and without saturation (harmonics), Fig. 12 and Fig. 12, respectively.

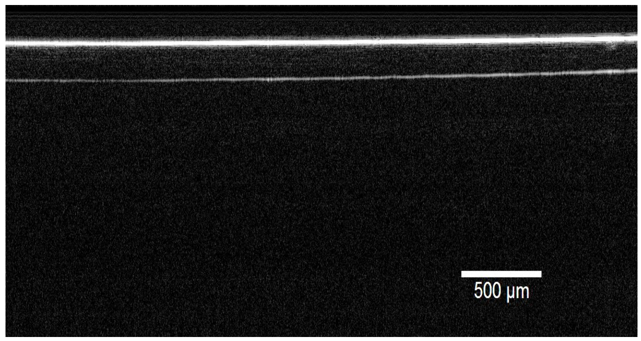

Fig. 11: Image without strong saturation of a vibrating mirror. The movement is not visible at the 1st harmonic and is very sbtle at the 2nd .

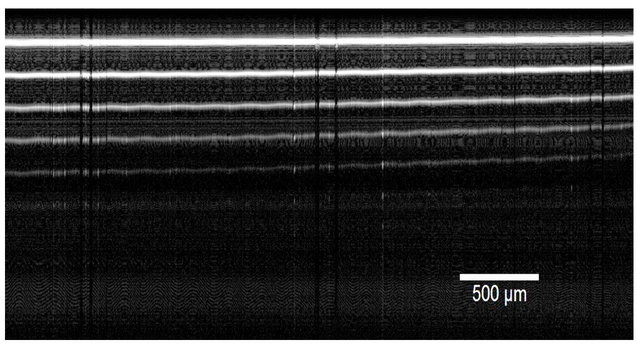

Fig. 12: Saturated image of a vibrating mirror. The movement amplitude becomes bigger for higher harmonics, making easy to appreciate the pattern in the image.

In the figure Fig. 11, even when trying to avoid any saturation as possible, still possible to see that the second harmonic is present, however is not possible in the fundamental surface (1st harmonic) to visualize any movement. At the Fig. 12, on the other hand, at higher harmonics (3rd ,4th and 5th) the sinusoidal pattern can be seen and even could be measured. Zooming the image, was possible to estimate the peak to valley height as 3(1) pixels at the 5th harmonic, the OCT system is calibrated as 3.088 µm per pixel in the Z axis, resulting 1.85(61) µm of peak to valley distance. There was no other comparative method to confront results for this experiment.

4. CONCLUSIONS

Through this study was possible to demonstrate practical applications of the harmonic features analysis aiming better visualization of features that is not well resolved in the traditional OCT image due its poor axial resolution. The mechanism and its validation was already discussed in previous work[6], where only a step height standard was used. The concern here was to demonstrate the potential of this technique in routine situations of surface inspection and also movement quantification using OCT.

For the roughness evaluation, was demonstrated that more accurate values could be retrieved through the harmonics analysis. The 5th order presented both: more accurate and precise result, 10.25(10) μm, when comparing with the reference value of 10.044 μm, while at the 1st order the result was 11.21(97) μm.

Also we demonstrated the usability of this approach for angle measurements, but for this case we could not get compatible measurements between white light profilometry and OCT. Two hypotheses could lead for this mismatch: The calibration of the OCT spectrometer was not precise; leading to appreciable errors for high amplitude reliefs or the there was variation of the edge angle across the blade. In this way further study needs to be performed to make this point clear.

The movement evaluation experience, revealed sub resolution shifts of a metallic surface. The amplitude was evaluated as 1.85(61) μm, at the 5th order, far below the system resolution, although for this measurement we did not have a reference value for comparison was interesting to visualize features that was not present at the 1st order.

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