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MASTER THESIS WORK

Performance characterization of an optical profiler through the measurement of the linearity deviations of the vertical scanner

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Performance characterization of an optical profiler through the measurement of the linearity deviations of the vertical scanner.

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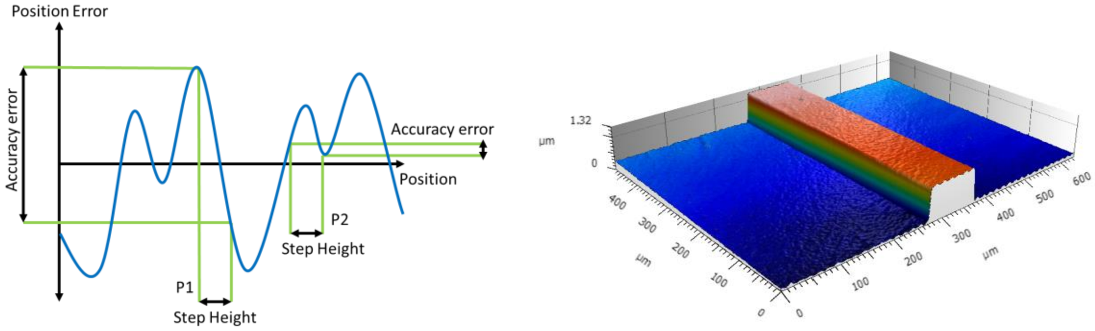
Abstract. Nowadays the determination of the accuracy and repeatability of an optical profiler is done by performing several repetitions of a step height measurement and calculating the accuracy error (mean) and the repeatability error (standard deviation) of the data obtained. This process is inefficient, time consuming and highly dependant on the non-linearity error of the vertical stage which highly determines the values of both accuracy and repeatability. In this paper we show the existence and further characterization of non-linearities in the movement of the vertical scanner of an optical profiler and their influence in the determination of the optical profiler specifications.

Keywords: Laser interferometry, Motor characterization, Confocal Microscopy, Imaging Systems

1. Introduction

Confocal microscopy is one of the main techniques used nowadays for surface metrology as it provides an increased optical resolution and contrast by using a pinhole that blocks the light that comes from regions that are out of the objective focal plane. Typically, a confocal microscope produces multiple two-dimensional images taken at different positions through the optical axis (usually known as the Z-axis). Consequently, each image pixel shows a response on the Z direction known as Axial Response where it's maximum corresponds to the position where a given pixel is located on the focal plane of the objective. By computing the Axial Response of all the pixels and later the Z position corresponding to the maximum, the surface is reconstructed [1]. To do so, the in-plane scanning of the surface has to be coordinated with the scan in the Z direction.

Usually, the scan in the Z direction is done by a linear stage which its movement is controlled by a motor (motorized stage) or a piezo (piezo stage). The vertical scan determines the Z values of the surface and therefore is the key component in confocal microscopes that defines its accuracy and repeatability. Any type of non-linearities and lack of accuracy of the stage will cause an erratic reconstruction of the surface topography. The causes of non-linearities are almost endless, tilt between the objective and the optical axis, vibrations, acceleration and deceleration of the motor and gear defects to mention a few of them. To have a deeper insight on how the non-linearities affect the measures we can imagine a situation similar to the one represented on Fig. 1a. The position error (difference between the position where the stage should be and the real position) is represented on the vertical axis of the plot while on the horizontal axis we can see the position of the stage. If we perform the measurement on the position P1 we will have a small error associated to the motor non-linearity. On the other hand, if we measure at position P2 we have a very large error associated to the measurement. As can be seen the plot follows a completely unknown profile.



(a) (b)

Figure 1. (a): Accuracy error on a step height measurement located at different positions of the Z axis. (b): 3D topography of a 1µm step height.

Nowadays, the characterization of optical profilers such as confocal microscopes is done by measuring a traceable standard (usually a step height similar to the one in Fig. 1b) several times in order to determine the average value (accuracy) and the standard deviation of the measurements (repeatability) [2]. This process is time consuming and very sensible to any source of errors that can modify the measures.

When measuring a step height, we can state to opposite cases depending on the position of the stage when we perform the measurement. If the bottom and the top of the step fall in positions of the stage where the difference in position error between them is close to zero, the accuracy error will be very low. On the other hand, we can have the bottom or the top part falling in a peak of the plot and the other position of the step on a valley (or vice versa) which will lead to a maximum error in our measurement [3]. Thus, the non-linearities will have a direct effect on both the accuracy and repeatability of the measurements, and the precision and behavior of the system will depend on the position of the motor when the measurement of a standard step height is made.

The goal of this work is to characterize the aforementioned non linearities. To do so, the main idea is to compare the real stage movement with the theoretic movement. At the end, it would be desirable to obtain a very precise curve of the motor non-linearities along all the stage path to be able to characterize which zones have the behavior with lower non-linearities.

Firstly, it has to be stated if the non-linearities that appear when the motor moves are repetitive (i.e. the non-linearity curve is the same for each measurement repetition) and also, the effect of backlash in the capability of the motor to be located at the desired position. The motor backlash can be defined as “the maximum distance or angle through which any part of a mechanical system may be moved in one direction without applying appreciable force or motion to the next part in mechanical sequence”. A schematic representation can be seen in Fig. 2. It is very common in mechanical parts that involve the gears of the reducers in motors. To correct this difference between theoretical and real position, motors move an extra distance to overcome the backlash effect and stop in the desired position.

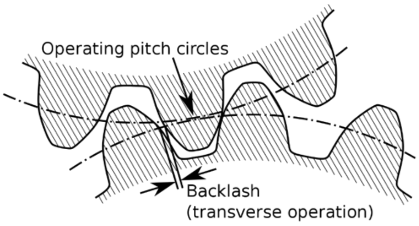


Figure 2. Illustration of the backlash distance that appears on the gears of a motor.

Different techniques will be used to characterize what has been explained in the previous lines. Firstly, an initial approximation will be done with a tilted mirror and then more precise measurements will be performed with the help of a laser interferometer:

a) *Tilted mirror:* In this first approach, a flat optical mirror (SiC) will be placed with a certain tilt angle and several repetitions of measurements of the mirror surface will be done in at least 0.5mm range on the Z axis. To do so a movement along the X axis of many field of views is required in order to cover the Z height of the mirror. As the mirror is supposed to be very flat, the errors on the measurement will mostly come from the non-linearities in the Z scan. It has to be taken into account that the movement on the X axis will induce also another source of error as we cannot ensure that the objective will be positioned on the same position in X each repetition and also there will be differences among consecutive fields of view. Thus, we shall expect to see a shift in X among the different repetitions of the non-linearity profile. This experiment will help us to have preliminary results in a rapid and easy way.

b) *Measurement of the stage movement with a laser:* In this case, the main idea is to aim a laser interferometer on the turret where the microscope objectives are placed and to record the distance between the laser interferometer and the turret. Laser interferometry is a very well-known technique that is commonly used to determine distances with very good precision. In our case, instead of aiming the laser to a mobile mirror, we will aim the laser to the objectives turret of the optical profiler that will be moving when a scan in the Z direction is performed and thus we will be able to determine the relative position between the two laser paths. This technique will allow us to know the real movement of the stage in the vertical direction with extremely good precision and we will compare it with the theoretical position where the stage should be at each moment (calculated with the speed at which the stage moves and the time that the movement lasts). This will allow us to plot curves of non-linearities with high detail, similar to the ones shown in Fig. 1a and perform simulations via software that will be used to determine the accuracy and repeatability when performing measurements of step height standards.

Lastly, measures of real step height standards will be performed at different positions of the Z direction of the stage. The measures will be repeated 10 times to compute its average and repeatability. These values are compared with the data obtained when recording the movement of the turret with the laser. In this way we will be able to correlate the characterization of the non-linearities done with the laser with those of a real step.

2. Methods

Several components, systems and devices has been used in the following work:

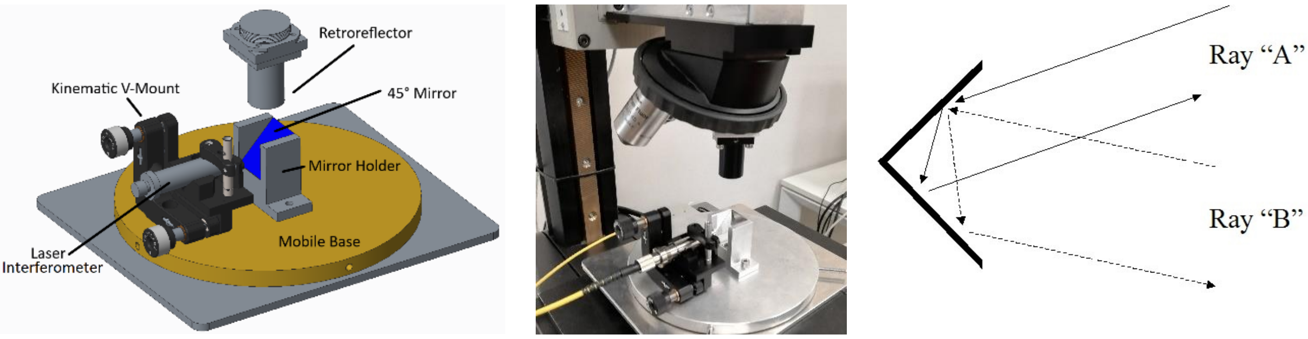
- Optical profiler PLμ-Neox from Sensofar-Tech.SL
- SiC mirror
- Laser interferometer IDS3010 (1530nm) with M12/C7.6 Sensor Head, both from Attocube (Germany)
- 45° aluminum mirror from ThorLabs (USA)
- Kinematic V-mount from ThorLabs (USA)
- Vertical Z stage M-MVN50 from NewPort (USA)

2.1. Tilted mirror

In this first experiment a SiC mirror is fixed in a certain tilting angle that allows us to perform measures of the surface. We have a limiting tilt angle of the mirror as we need a minimum of light reflected back to the objective, high tilting will cause the light rays to not be reflected back and thus we will not be able to take a measure. The limiting angle is calculated empirically and later measured giving a tilting angle of 5.19°. In order to perform a scanned distance in the mirror Z direction equivalent to 0.5mm we have to perform 10 fields of view of the microscope with a 20x objective (each of them of 0.65mm in the X direction) and a further stitching treatment between the images and leveling.

2.2. Laser interferometry

To carry out the experiment explained in the introduction part we followed the following procedure. Firstly, a market study was done in order to evaluate the different laser interferometers available in the market and select the one that fits our needs the best, which ended up being the IDS3010 (1530nm) with the M12/C7.6 Sensor Head, both from Attocube that allows a resolution down to 1pm, much less than what we need. To be able to incorporate the laser to the optical axis of the confocal microscope, a 45° mirror from ThorLabs is bought and an aluminum mirror holder is designed with CAD and later manufactured to fix the mirror on to a mobile base. Moreover, a kinematic V-mount from ThorLabs is mounted to allow us to both, fix the laser and be able to control precisely the laser orientation on the X-Y plane. Lastly, a retroreflector is fixed on the system's objective turret to complete the interferometer, the whole setup can be seen in Fig. 3a and 3b. The retroreflector is used instead of a typical mirror to ensure that the light goes back to the fiber to produce the interference regardless of the incidence angle. The retroreflector will reflect the light parallel to the incidence direction as seen in Fig. 3c.



(a) (b) (c)

Figure 3. (a) Set up designed with CAD showing the laser, mirror and retroreflector placements, (b) Real image of the set up shown in 3a, (c) Working principle of a retroreflector.

2.3. Software development

To acquire and process the data we developed two software: A software based on Python that allows us to analyze the data obtained from the non-linearity profiles and to simulate the accuracy and repeatability that will have a step height standard. In the software it is possible to change the step size and calculate the mean value and repeatability of the step at each position of the non-linearity profile. The standard deviation is computed from a set of height values calculated within a small position window around the top and bottom positions of the step. This position window is typically the backlash error of the linear stage. We also programmed a C++ executable that allows us to control the optical profiler to perform scans along the Z direction in steps or continuous, change the speed of the scanning and the most important: to record the position measured by the laser in temporal steps. To develop the aforementioned programs an intensive work in coding was done.

2.4. Step height measurements

We performed ten confocal measures of two traceable step heights from VLSI Standards Inc. models SHS-9400 QC and SHS-50.0 Q which are 941.6 ± 5.5nm and 48643 ± 0.263nm respectively. After the 10 repetitions are made, the motor is moved up 3, 5 or 20µm and then the step is independently moved up by using a Vertical Z stage M-MVN50 from NewPort controlled with a micrometer. Consequently, we were able to measure the step at different positions of the stage and calculate the mean and standard deviation of repetitions at each Z position and then compare it to the mean and standard deviation plots calculated with the data obtained with the laser in the previous section.

3. Results and Discussion

3.1. Tilted mirror measurements

As explained in the point 2.1, the surface profiles obtained are leveled in order to extract the tilting angle and thus obtain only the non-linearities (i.e. the differences between the real and theoretical position). As we have performed eight repetitions of the same measurement of 10 field of views we can compare the profiles among them as seen in Fig. 4. We can see that they follow a similar profile with slight differences probably caused by the non-linearities in X explained in the introduction, but we do not obtain a perfect match which would be the ideal case. Moreover, we can appreciate that a certain oscillating behavior is observed. These oscillations and non-linearities will affect the measurements as we saw in Fig. 1a, for example a measurement located in a high slope position of Fig 4 (2.3 - 2.5mm in the horizontal axis) will have a measurement error of nearly 500nm while a measurement done in a low slope (2.5 - 3mm) will have a nearly zero error.

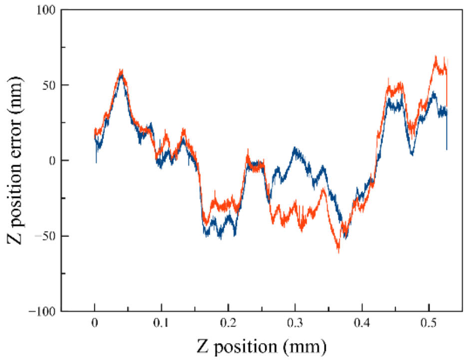
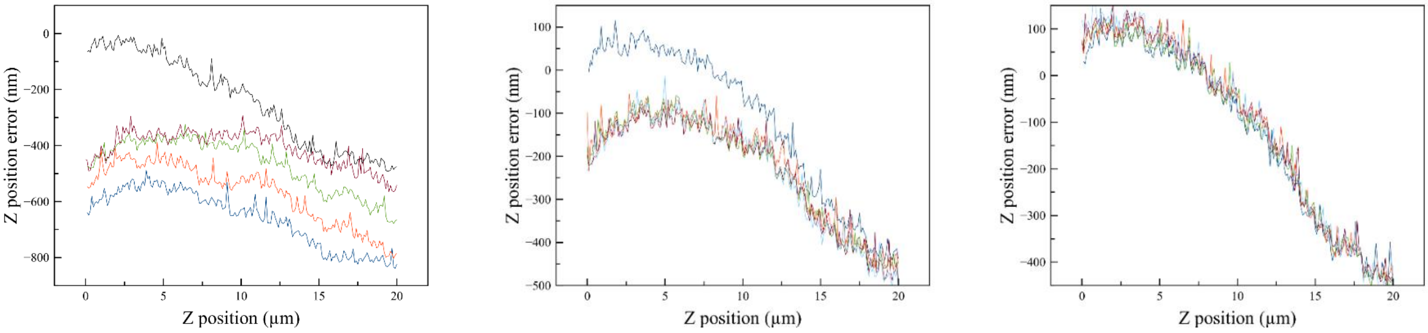


Figure 4. Plot showing the position error assigned to each Z position of the vertical stage for two of the eight repetitions.

3.2. Laser Interferometry measurements

With the setup explained in 2.2 and the software developed we are able to perform very precise measurements and store the data for further analysis. Thus, the following experiments are all performed using the laser.

We start studying the effect of backlash as we had to be sure that the non-linearity curve that appears when doing a scan is repetitive if we perform the scan several times. If the curve differs from scan to scan it would be impossible to characterize it. Moreover, we wanted to ensure that the backlash effect could be corrected, otherwise each time that a scan is done and the stage is taken back to the theoretical initial position the motor would be placed in a different position which will cause another position of the motor in the non-linearity curve. To do so, we performed several scans emulating a confocal measurement (i.e. steps in the up direction and going back to the original position in a single step) with a certain number of repetitions without and with different values of backlash correction, which adds an extra movement (up and down) to the end of the commanded movement in order to overcome the backlash distance intrinsic of the motor architecture. The results are presented on Fig. 5.

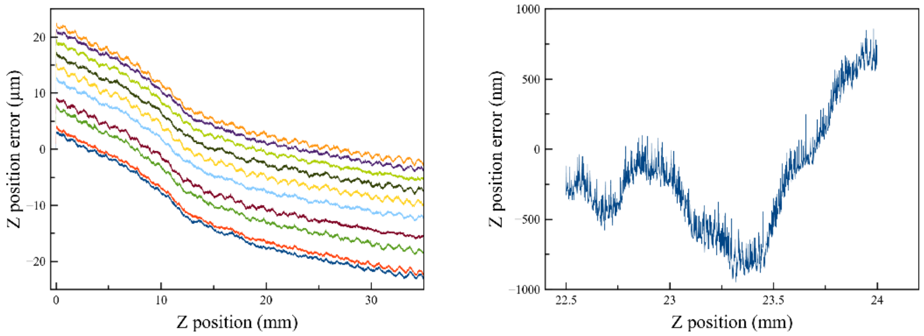


(a) (b) (c)

Figure 5. Plots showing the backlash effect on the position error for: (a) No backlash correction, (b) Backlash correction of 3.5µm, (c) Backlash correction of 50µm.

As can be seen, the scans without backlash present different paths for each repetition due to the fact that when the motor ends the first scan and goes back to perform the second scan it stops before reaching the desired position. This is reflected in the big decrease of the position error (theoretical minus real position) which implies that when the stage starts to turn back, the backlash distance causes a delay of the real position respect the theoretical one, this will produce that when we should be again at the initial position (0nm) the stage is at 800nm producing a negative error in the vertical axis of the plot (-800nm). Consequently, from the plots we can determine that the backlash value of the motor used is around 600-800nm. On the other hand, when the backlash correction value is set to a value larger than the 800nm we can appreciate a significant improvement. The backlash compensation completely disappears when the correction value is set to 50µm.

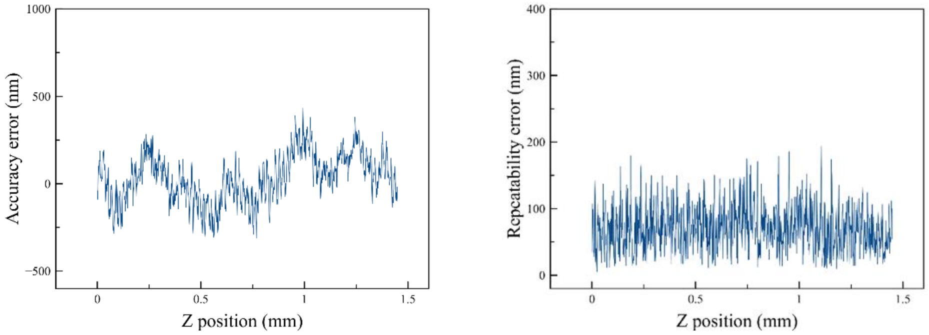
Moreover, a further important conclusion is that the non-linearity curve is repetitive in shape for each series of measures. This conclusion is key to proceed with the research, a repetitive non-linearity implies that the main source of non-linearities is the motor behavior and that it does not change from one measure to another which means that it can be characterized and correlated to the results obtained in real measures. According to the previous results we decided to characterize a big range of the motor movement in the Z direction with as much detail as possible to identify the non-linearities. To do so, we performed several repetitions of a measurement of nearly 40mm in the Z direction, which corresponds to the maximum movement range of the motor stage in order to know how the motor behaves in all of its range. The results are presented on Fig. 6a.



(a) (b)

Figure 6. Position error plots obtained with laser interferometry: (a) For a 40mm range, (b) For a 1.5mm range.

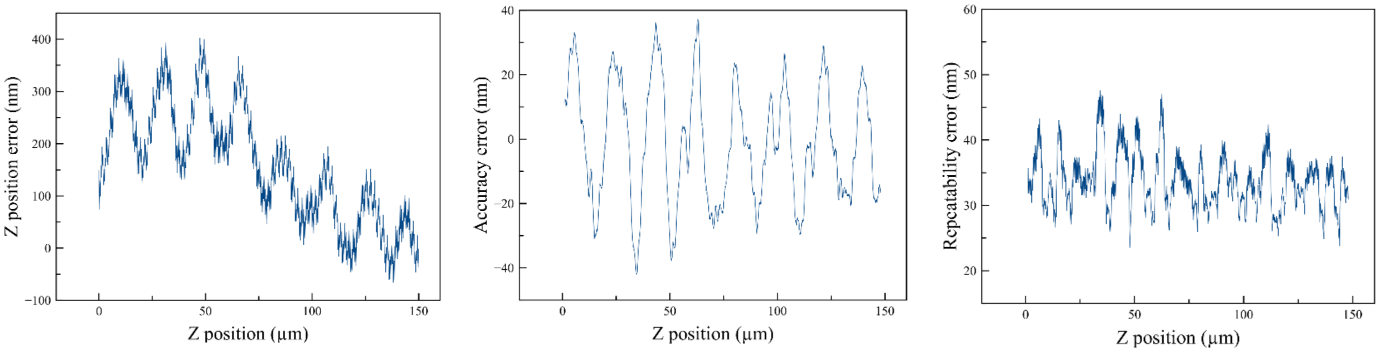
As can be seen, the repeatability is good but we can see that each repetition starts in a different point leading to a significant position error at the end of each iteration. Later on, we selected a smaller range of 1.5mm at the center of the total 40mm in order to perform a more detailed study. We measured the position in 1µm steps and we also performed five repetitions, the average of those repetitions can be seen in Fig. 6b. This profile shows the error in the positioning for each position in the Z axis. As can be appreciated, a non-linearity profile is superimposed with a large frequency. As explained in 2.3 we also have the option in the developed software to compute the accuracy and the repeatability for each position that we would get with different step sizes and taking into account or not the effect of the backlash as shown in Fig. 7a and 7b.



(a) (b)

Figure 7. Simulations performed with the software developed on the 1.5mm measure: (a) Accuracy error at each Z position when using a 50µm step height, (b): Repeatability obtained at each Z position with a 50µm step height.

As can be seen, the results obtained are quite noisy and it is hard to give a physical interpretation of what we are seeing. To overcome this, we decided to perform a smaller measurement of 150µm measuring the distance between the laser and the turret every 100nm in order to obtain a high level of detail in the profile and in that way to be able to see the superimposed frequency mentioned before. The results are presented in Fig. 8.



(a) (b) (c)

Figure 8. (a) Position error plot for a 150µm range measured every 100nm, (b) Accuracy error simulation for a 1µm step height, (c) Repeatability error simulation for a 1µm step height.

We can see that the position error shown in Fig. 8a presents a sinusoidal behavior with 20µm period approximately. Moreover, when we zoom in we can see another well-defined frequency with 2µm periodicity and a very small one of 0.5µm. Those frequencies also appear at the plot corresponding to the measurement accuracy at each position of the stage (Fig.8b). Consequently, a very important physical consequence arises from this fact: the error that we will have when measuring a step height will be highly influenced by these periodicities if the step size is comparable to the periodicity period.

To ensure the existence of the frequencies mentioned in the previous lines, a frequency study was made by performing a study based on the FFT of the plot Fig. 8a. The results are shown in Fig. 9a, where on the vertical axis is presented the magnitude of the frequencies and the X axis simply enumerates the number of frequencies detected ranged from small to high frequencies (i.e. large to small periods).

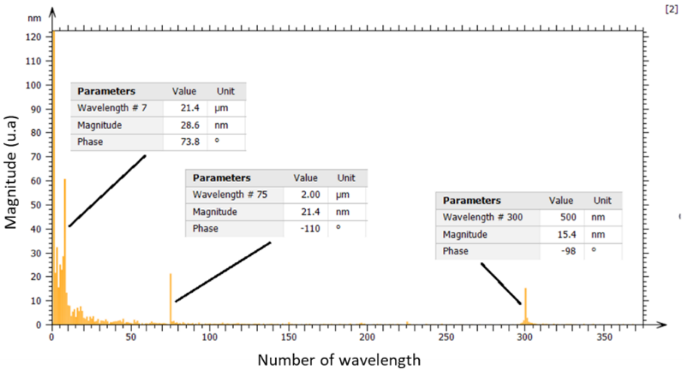
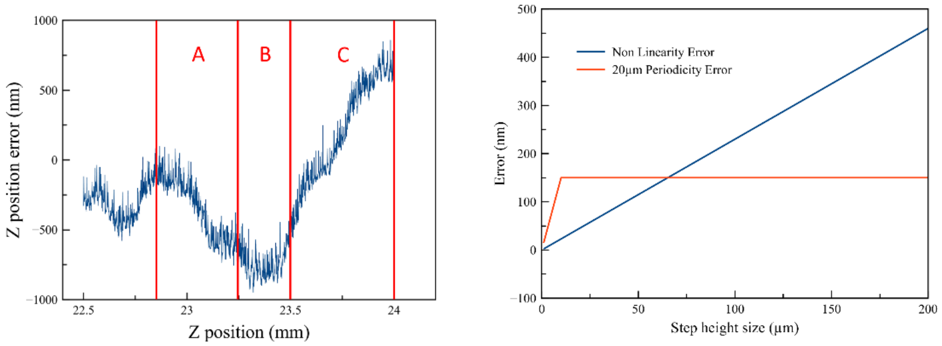


Figure 9. Plot showing the different frequencies and their amplitude obtained with the FFT of figure 8a.

As can be seen, three frequencies are well defined and correspond to 20, 2 and 0.5µm periods respectively, which confirms the existence of a periodic behavior in the motor. The motor used in the optical profiler is a two-phase step motor that moves in steps of 0.5µm, every four steps the motor has moved a complete gear. This implies that the frequencies that have a periodicity of 2 and 0.5µm can be due to the repetitive behavior of the motor every 4 and steps while the frequency with period 0.5µm is produced for each single step. Otherwise, we are not sure about the origin of the 20µm frequency.

Now we will proceed to study the effect of the non-linearity plot (Fig. 6b) and the superimposed periodicities (Fig. 8a) when measuring a step height. We will select always the worst-case scenario (i.e. the zones with largest slope of the plots) in order to calculate the maximum error in the measurement just as in Fig. 1a. Starting with the non-linearity plot (Fig 6b) we have a maximum slope of 2.3nm/µm in a Z range of 500µm marked as C in the figure. This implies that if we measure a step height in that region we will obtain an error equal to the product of the slope and the step size if the step is smaller than 500µm. The maximum error of 1.5µm which corresponds to the full height of the maximum slope zone will appear for steps of 600-700µm. In contrast, zones A and B will have a negative error (due to the negative slope) and a small error (due to small slope) respectively. Looking now at the 20µm frequency (Fig. 8a), the maximum slope is 15nm/µm corresponding to the half of the period (i.e. a 10µm range in Z). Again, we will have an error equal to the product of slope and step height if the step is smaller than 10µm. We will have a 150nm maximum error corresponding to the height of the maximum slope region if the step measures 10µm. Lastly, the periodicities of 2 and 0.5 µm will only affect measurements of steps smaller than 1µm which do not fit our study case. A comparative plot can be seen below:

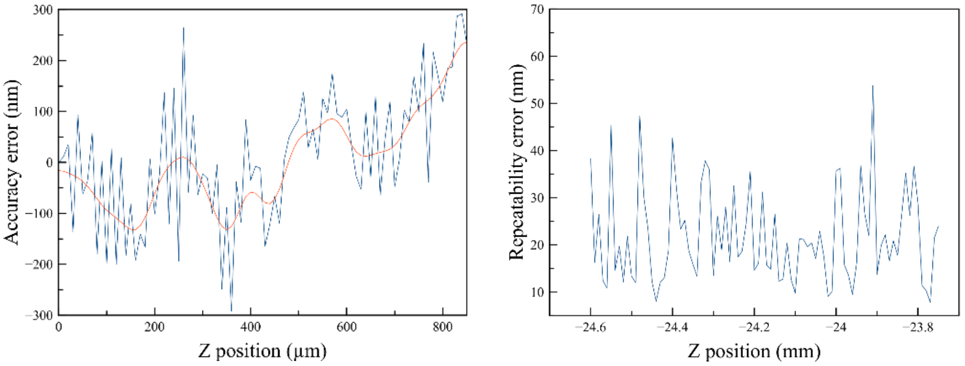


(a) (b)

Figure 10: (a) Non-linearity plot showing the different slope zones and their effect on the measure accuracy. (b) Plot showing the relevance of both the non-linearity error (blue) and the error associated to the 20µm periodicity (red) for different step sizes. Note that over 75µm the error associated to the 20µm periodicity is negligible.

3.3. Real step height measures

In this section, we wanted to confirm how the frequencies that appear in the error position of the stage affect when a real measurement is done. To do so, we simulated the procedure that is done to determine the system accuracy and repeatability which consists in measuring 10 times a step height standard and compute the mean and standard deviation of the heights measured. Those values have to be below certain thresholds in order to consider that the optical profiler works properly. The measures are done following the procedure mentioned in the 2.4 section starting at the same position of the stage where the laser measurement of 1.5mm (Fig. 6b) was done in order to characterize the same motor working zone. The most detailed scan is done with the step of 48.643µm by performing 10 measurements every 10 microns until covering a range of nearly 1mm. Once the measures are done, the accuracy and standard deviation plots are computed:



(a) (b)

Figure 11. Plots obtained from real step height measurements: (a) Calculated accuracy error at each Z position before (blue) and after (red) applying a Gaussian filter, (b) Calculated repeatability error at each Z position.

As can be seen, both plots are quite noisy and thus hard to compare. To overcome that, we performed a Gaussian filtering to get rid of the large frequencies on Fig. 11a. This filtering is done as we can assume that the large frequencies come from many sources of error when the measures were done (uncontrolled atmosphere, people talking and walking and air moving on top of the sample among others).

We also filtered the accuracy error measure done with laser (Fig. 7a). The physical reasoning for performing such filtering is basically that when a confocal image is taken, the axial response is computed by a parabolic fitting with three points and further smoothing. Moreover, the objective depth of focus induces a measurement error of ~1µm. For this reason, we can filter the accuracy plot to get rid of the large frequencies as they will be averaged in measures taken with confocal. Consequently, both the accuracy error plots obtained from the laser measurement of the stage movement (Fig. 7a) and the one corresponding to the accuracy error calculation of the confocal measurements (Fig. 11a) done at different positions in the Z axis are filtered using a Gaussian function and the outputs are compared.

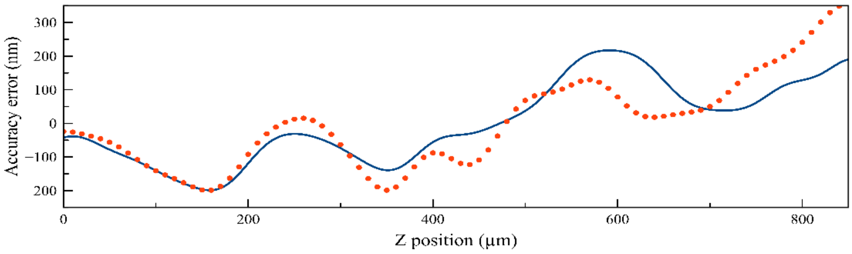


Figure 12. Comparison of the accuracy error plots after applying filtering. Solid Line: the accuracy error plot obtained via simulation of a 50µm step on the position error curve obtained measuring the stage movement with laser interferometry. Dotted Line: the accuracy error plot obtained by computing the mean of 10 confocal measurements in each position of the stage Z axis.

It is safe to say that the two plots are practically identic, it only seems to be a factor that produces a “compression” of the dotted line. This implies that the measurements done with laser on how the stage moves are directly determinant on the real measurements accuracy and repeatability. Moreover, a single measurement with the laser of the whole stage movement range will allow us to know the position error for each position of the stage in Z and thus determine which zones are optimal for performing measures (the ones that have null slope). Furthermore, by using the software developed we can compute, for different step sizes, the accuracy and repeatability that we will obtain at each Z position before doing any measurements of the real step standards.

4. Conclusions

We have observed, characterized and understood the non-linearities that appear in the movement of the vertical stage in an optical profiler with two different techniques. We have also determined and corrected the backlash effect when repetitions of the same measurements are done.

The stage non-linearities (deviations from the ideal linear behavior of the motor stage) show an oscillating behavior which causes that certain positions in the Z axis present a large error in the measures compared to others. Both the accuracy and repeatability of the optical profiler system are highly influenced by the mentioned non-linearities.

We conclude that the physical cause of those repetitive non-linearities is the stepper motor which moves in steps of 0.5µm that cause the appearance of periodic behaviors with periods of 0.5, 2 and 20µm. We also have seen that the non-linearity curve dominates the measurement error for steps larger than 75µm while the 20µm periodicity affects strongly small steps.

We compared the accuracy error calculated for each position in the Z axis obtained with the laser measures and by measuring the mentioned step and the results are almost identic. This implies that the non-linearity curve obtained with the laser in a single measurement of the whole stage range is the same than the one that will affect the measurement of real samples and thus we can characterize with a single measure the zones of the stage that will present a better accuracy and repeatability.

5. Further work

Step height standards will be needed to be measured with higher magnification objectives in confocal mode, such as 50X and 150X. This will completely change the frequencies of the linear stage that are affecting the repeatability, since these objectives scan at predefined steps of 0.2 and 0.1 micron respectively. There will be also the need to understand the effect of the non-linearities to Coherence Scanning Interferometry, which scans at steps of λ/8 (typically on the order of 70 nm), at continuous speed.

6. References

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