Stability & Repeatability of Optotune Liquid Lenses

Author: Daniele Ghedalia (daniele.ghedalia@optotune.com)

Abstract

In the present paper we demonstrate the outstanding performance of Optotune focus tunable lenses. Specifically, a telecentric Electrical Lens Module integrating Optotune's EL-16-40-TC-VIS-5D is used to demonstrate the liquid lens **stability** and **repeatability** performance in a lens system possessing extremely shallow Depth of Field (DoF).

Two distinct use-cases are explored, as shown in Figure 1: the first consisting in long-term holds - lasting several days - where the liquid lens focal power is kept constant; the second consisting in numerous, random, and quick (in the order of milliseconds) jumps away from and back to a pre-defined focal power value. While case A is representative of inspection applications where re-focusing is seldom needed, and **stability** mostly relies on the material and actuation properties of the liquid lens, as well as on Optotune controller's thermal compensation, case B is relevant for more dynamic utilizations of the liquid lens, where a calibration look-up table is used to consistently and repeatedly focus at pre-determined working distances, or contrast-based autofocus routines are employed. In this latter case, the **repeatability** performance of the liquid lens is tested.

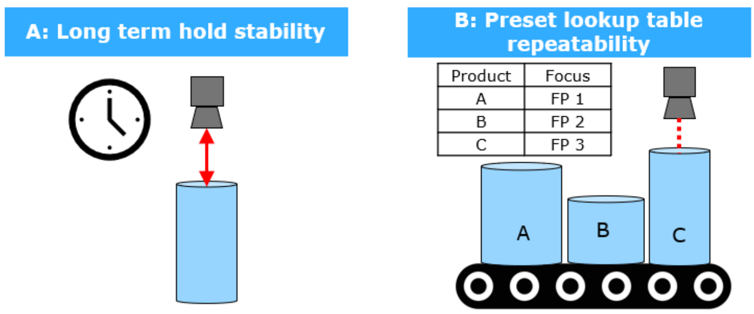

Figure 1: Illustration of the two use-cases. Case A (left) replicates a long-term hold at a unique focal power; case B (right) replicates fast re-focusing at pre-determined focal power values.

The results of these tests show that Optotune liquid lenses can be confidently and reliably used in demanding applications requiring the highest degree of stability and repeatability, such as electronic and semiconductor inspection, die bonding inspection, metrology etc. Both stability and repeatability were found to be within a range of +/- 10 mdpt.

Experimental setup & methods

Figure 2 shows the experimental setup for the imaging tests. Sill's telecentric 2x lens S5VPJ6420 with EL-16-40-TC-VIS-5D integrated was chosen, given the relatively high magnification and consequently shallow depth of field (≈ ± 50 µm at a numerical aperture NA of 0.18 and f-number of 5.5) that would normally be used in inspection applications such as semiconductors or metrology. To control the liquid lens, Optotune's four-channel industrial controller ICC-4C was used. The camera was a Basler acA2040 – 55um with a pixel size of 3.45 µm and a resolution of 3.2 megapixels (sensor format 1/1.8"). A blue backlight by CCS was used.

To monitor the stability and repeatability (case A and B, respectively) of the liquid lens focal power, a contrast-based method was used. A Ronchi ruling target (Figure 3) with a spatial line frequency of 100 lp/mm was used, resulting in a frequency of 50 lp/mm in image space. The contrast metric is computed using a Sobel filter in both x and y directions, using the following formulas:

```python
sx = cv2.Sobel(img, cv2.CV_64F, 1, 0, ksize=5)
sy = cv2.Sobel(img, cv2.CV_64F, 0, 1, ksize=5)
magnitude = cv2.magnitude(sx, sy)
contrast_metric = magnitude.mean()
```

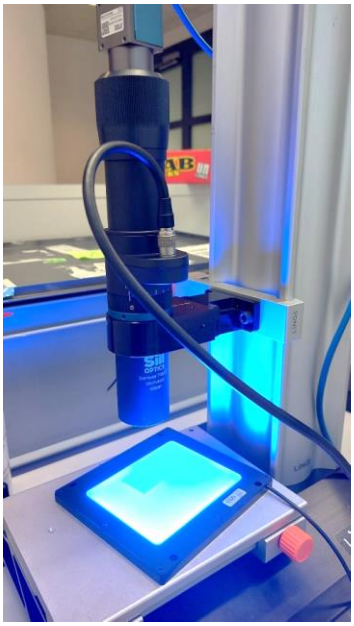

Figure 2: Experimental setup showing Sill's 2x telecentric lens S5VPJ6420 with EL-16-40-TC integrated.

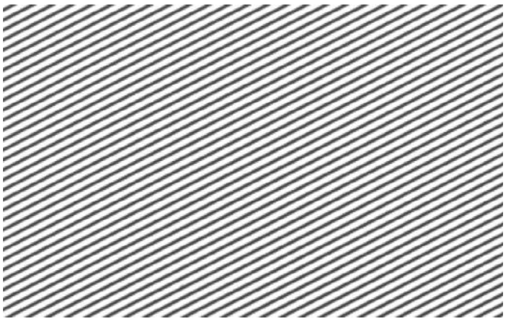

Figure 3: Image of the Ronchi ruling target (50 lp/mm) used to compute contrast.

For both cases A and B, at the beginning of the experiment (for a specific working distance), a focal power sweep is performed, with a twofold purpose: on the one hand, this allows to find precisely the focal power corresponding to best focus; on the other, it later allows to correlate the drift in contrast to the drift in focal power during the rest of the experiment.

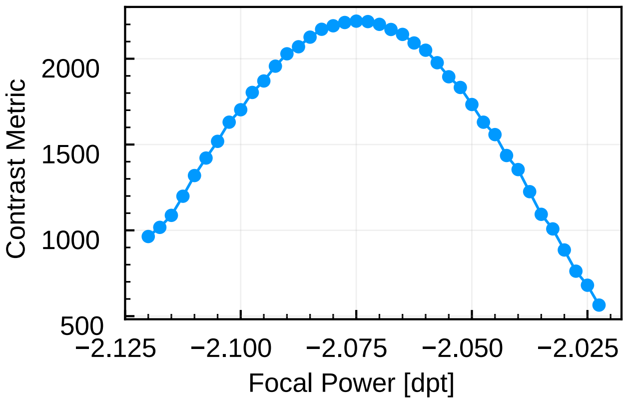

Figure 4: Example of contrast vs focal power calibration curve before the start of the tests

Use cases A and B are also replicated in an experimental setup where the liquid lens alone is tested, namely, a Shack-Hartmann sensor (SHS) is used to monitor the refractive power and wavefront error characteristics of EL-16-40-TC-5D.

Figure 5: Shack-Hartmann sensor with collimated light source

Case A: Long-term focal power holds (stability)

For Case A, long-term holds of four days were performed with focal powers of -2 dpt and + 2 dpt, corresponding to working distances of ≈ 76 mm and ≈ 60 mm, respectively. As shown in Figure 6 , the contrast of the image stayed within 5% that corresponding to the best focal power set at the beginning of the experiment. This corresponds to a maximum focal power drift of (±) 10 mdpt, as shown on the right side of the same Figure.

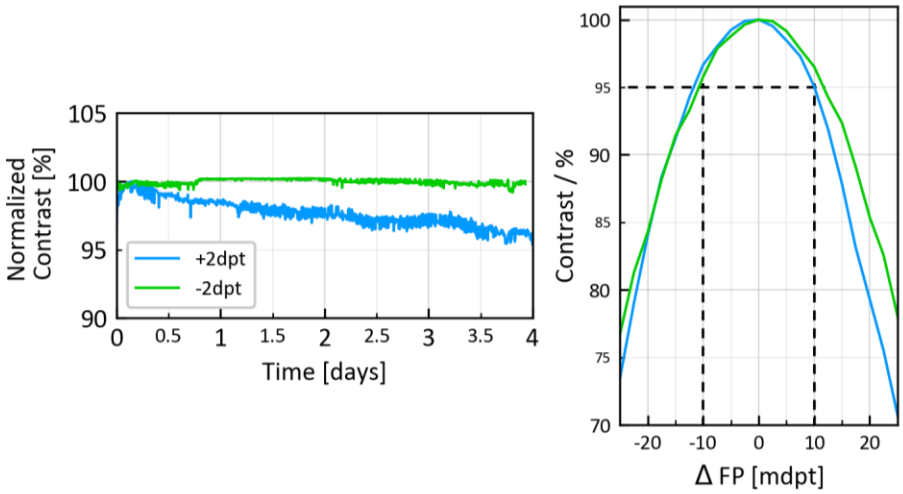

Figure 6: Result of long-term focal power holds at -2 and +2 dpt

The same kind of experiment was performed for 10 hours using a Shack-Hartmann sensor. Thus, external factors such as vibrations impacting the mount of the telecentric lens and drift of the other optical components could be neglected. The results shown in Figure 7 confirm the excellent stability of EL-16-40-TC controlled with ICC-4C, with its focal power staying within a range of ≈ 6-7 mdpt (≈ +/- 3.5 mdpt) for most of the experiment, with fluctuations being attributed mostly to noise affecting the Shack-Hartmann sensor.

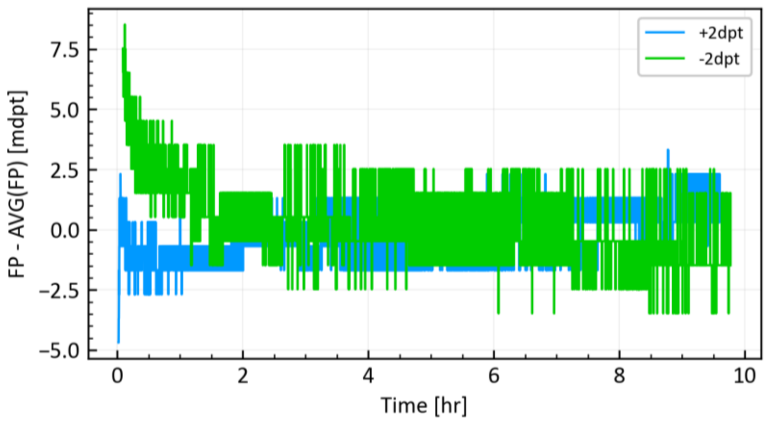

Figure 7: Result of long-term focal power hold using a Shack-Hartmann Sensor

Case B: Quick focal power jumps (repeatability)

For Case B, the lens was tuned away and back to the focal power corresponding to the best contrast at specific working distances. Focal powers of -2, 0 and + 2 dpt were used. The list of focal power jumps was generated within a range of +/- 2 dpt for the experiment at 0 dpt, and +/- 1 dpt for the experiments at -2 and + 2 dpt, respectively, where each distinct jump was repeated 10 times in random succession and was equal to a multiple of 0.25 dpt. Figure 8 shows, as an example, the random succession of focal power jumps for the experiment performed at 0 dpt. A settling time of 30 ms was used for each focal power jump before grabbing the image.

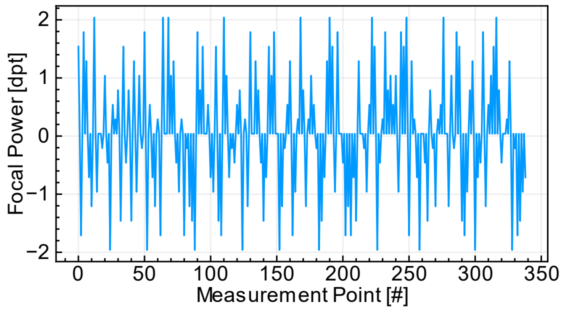

Figure 8: List of random focal power jumps to 0 dpt. Each jump is a multiple of 0.25 dpt and has been repeated 10 times.

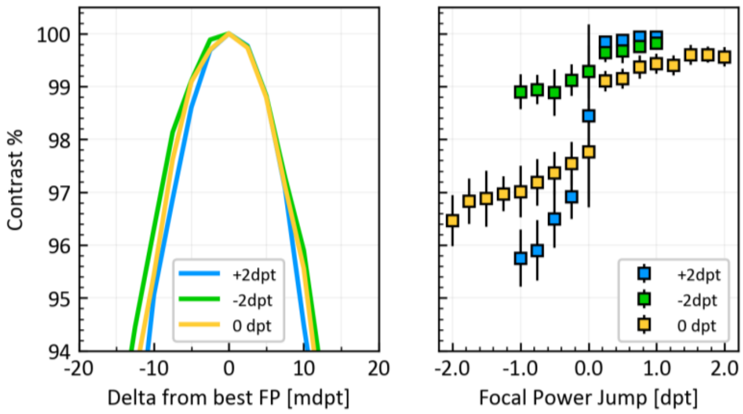

Figure 9: Results for the short-term repeatability tests performed at focal powers of -2, 0 and +2 dpt, respectively. By correlating the average and standard deviation of the contrast value obtained at different focal power jumps (right side) with the curves describing the relationship between contrast and focal power (left), it can be concluded that a repeatability within a range of +/- 10 mdpt can be achieved.

Figure 9 shows the results of these experiments by correlating the curve describing the relationship between contrast % and focal power (left) and the average and STD of the contrast % drop associated with each focal power jump (right). On the left of Figure 9, it can be seen that depth of field slighly increases as focal power decreases (the curve gets wider). This is due to the constant aperture being used in the different experiments, whereas the different focal powers create a small change in magnification, and therefore in numerical aperture. On the right of Figure 9, on the other hand, it can be seen that contrast % never dropped below 95%, which results into a repeatability within a range of +/- 10 mdpt at all working distances / focal powers.

A similar experiment, described in Figure 10, was conducted using SHS. As shown by the top left plot, the liquid lens was tuned randomly using its full tuning range (≈ -3 to 4 dpt), with “resets” at 0 mA in between jumps. A 3rd order polynomial fit was used to model the relationship between the random current jumps and the respective focal power values (top right). This “calibration curve” was then used to infer the focal power error, calculated as the actual value recorded by SHS minus the expected value from the fit.

The bottom left plot of Figure 10 shows that even at the most extreme negative and positive focal powers of EL-16-40-TC-5D’s tuning range, the focal power error stayed well within the +/- 10 mdpt interval, while the bottom right plot shows the distribution of focal power errors.

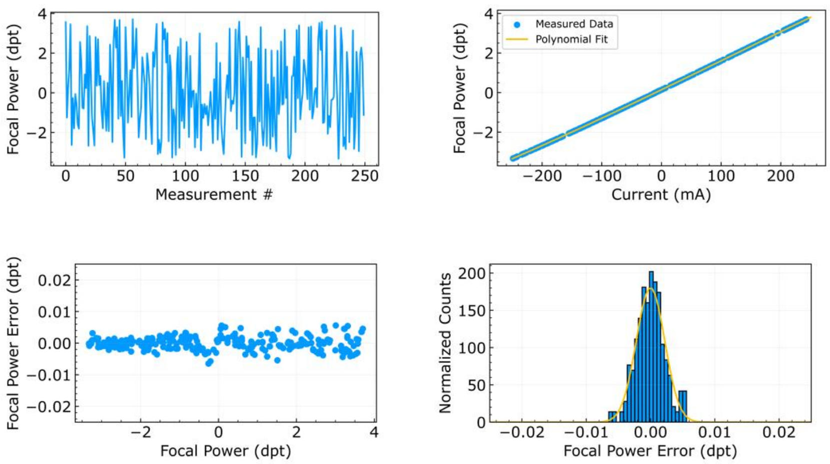

Figure 10: Repeatability test performed using SHS. 250 random current jumps were applied to the liquid lens, with resets to 0 mA in between jumps (top left), resulting in a calibration curve (top right) modeled as a 3rd order polynomial fit between current and focal power. The bottom left plot, displaying the relationship between focal power and focal power error from the calibration curve, shows that the error stays within a range of +/- 10 mdpt. The same is shown by the bottom right plot, displaying the distribution of the focal power error.

Conclusion

Optotune liquid lenses have already emerged as a remarkable solution for achieving rapid focusing in several domains, such as industrial and medical applications. Unlike traditional lens systems that rely on physically moving optical elements to adjust focus, Optotune's technology enables swift actuation by electrically altering the curvature of a core element containing a liquid trapped between a membrane and glass. This innovation ensures focus adjustments within an impressive range of 3 to 20 milliseconds, contingent on the clear aperture of the liquid lens, all while maintaining a compact form factor.

In specific applications where liquid lenses are employed for inspecting or measuring processes, distances, object planarity, and more, the key properties of repeatability during frequent and rapid focus adjustments and long-term focusing stability become paramount. Most importantly, it is essential to guarantee that the focal power of the liquid lens remains within the depth of field (DOF) of the overall lens system, which, particularly for high-magnification telecentric lenses commonly utilized in precision inspection and metrology, can be as shallow as a few tens of microns.

The tests presented in this white paper demonstrate that the Optotune EL-16-40-TC-5D can deliver this level of performance, offering both long-term stability and short-term repeatability within a range of +/- 10 mdpt. This level of performance is deemed satisfactory, even for the most demanding applications, such as electronic and semiconductor inspection, die bonding inspection, metrology, and more.

Please note that does not claim that a repeatability of +/- 10 mdpt will be achieved in all conditions and opera ting modes. For the official repeatability specifications, please refer to the lens datasheet.