Final Report
- Vacuum Support for LSST test plate -
- (OPTI523L Individual Project) -

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1. Executive Summary

The purpose of this technical memo is to report experimental results and simulation data for a vacuum support, which can be used for the Large Synoptic Survey Telescope (LSST) test plate. This memo consists of Introduction, Experimental setup, Results, Discussion, and Conclusion. The maximum difference between experimental data and simulation data was 9.6 [%] in Zernike 4th term and 9.9 [%] in Zernike 11th term at 275 [Pa], which met a requirement of 20 [%]. Therefore, it was validated that simulation about deflection caused by vacuum corresponded with experimental data.

2. Introduction

2.1. Background

Prof. Dubin et al. tries to measure the Large Synoptic Survey Telescope (LSST) secondary mirror by Fizeau type interferometer with 5mm gap as shown in Figure 1[1].

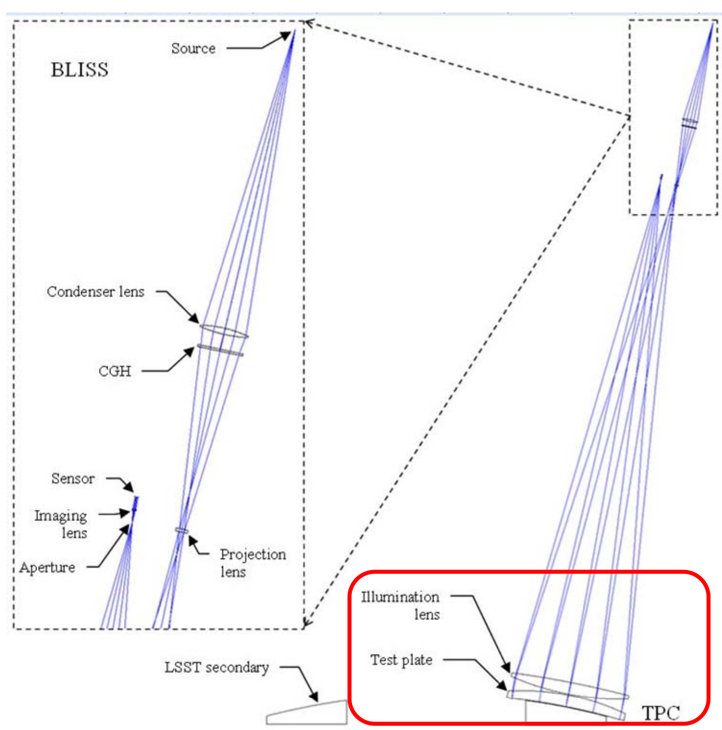


Figure 1. LSST secondary measurement system

In this case, the test plate shown in the area enclosed in red line would be bent because of the gravity. It becomes a problem, since the test plate itself would be flipped around after polishing the reference surface. Reducing an unexpected bending in the reference surface is required. For this purpose, evacuating air between the test plate and the illumination lens can be useful and effective for compensating the bending caused by the gravity.

Based on SolidWorks simulation about LSST, the deflection of the test plate caused by gravity can be optimized at 2200 [Pa] as shown in Figure 2.

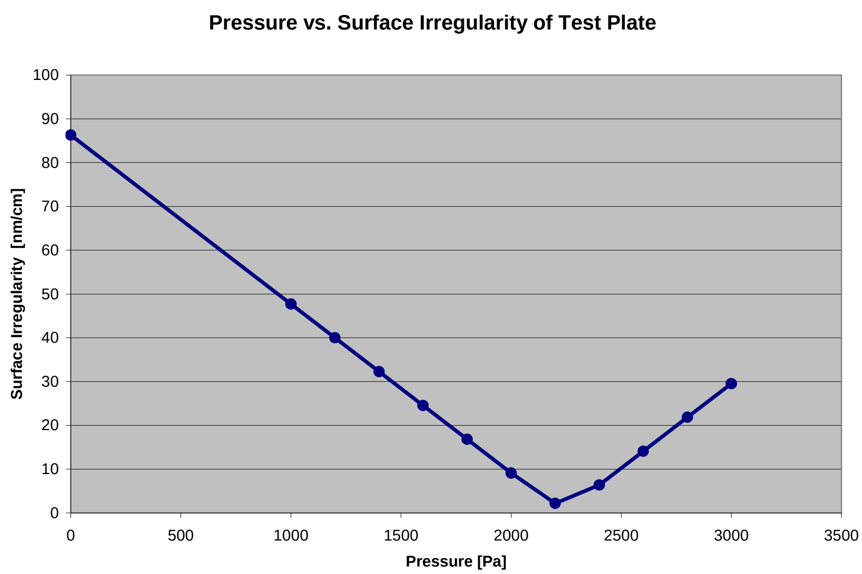


Figure 2. Relationship between pressure and surface irregularity of the test plate

In this case, the specification for the test plate surface is defined by a surface slope. If the differential pressure is 2200 [Pa], the surface slope is minimize to 2.19 [nm/cm]. Figure 3 shows the difference among interferograms for a perfect system (No gravity effect and No tolerance), a system with gravity effect and without pressure support, and a system with gravity effect and with pressure support. Figure 3 shows that the vacuum support for the test plate can reduce an error from 553 [nm] RMS to 2.1 [nm] RMS.

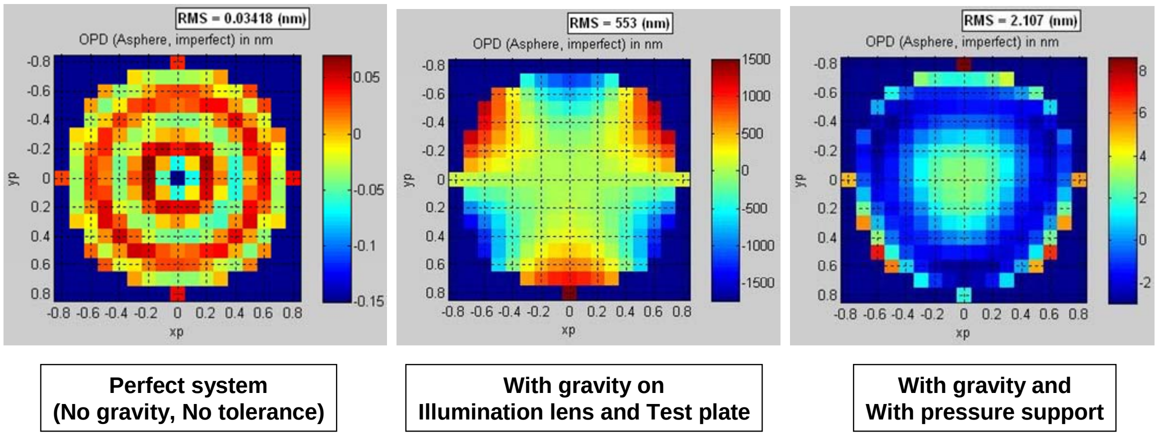


Figure 3. Comparison of interferograms

The scope of this individual project is to validate vacuum simulations correspond to experimental data within 20 [%] difference, and then, to show an effectiveness of the vacuum support in LSST model.

2.2. Procedure for the project

This individual project was implemented as the following steps.

Step 1. Hand calculation on LSST model

- Check a surface deflection of Test Plate caused by gravity
- Check a surface deflection of Test Plate caused by vacuum
- Summarize an effectiveness of vacuum technique

Step 2. Simulation on a flat surface model

- Design a flat surface model (~100mm in diameter, ~2.69mm in thickness)
- List the Zernike terms depending on pressure [Pa]

Step 3. Experiment on a simple model

- Set up the vacuum equipment, lenses or flat surface, and sealing material
- Measure the Zernike terms depending on pressure [Pa]
- Show simulation works based on the comparison of simulation data with experimental data

Step 4. Simulation on LSST model (in 523)

- Simulate wavefront caused by gravity (Solidworks -> Zemax)
- Simulate wavefront caused by vacuum (Solidworks -> Zemax)
- Show how much uncertainty caused by gravity can be reduced by using vacuum technique

3. Experimental Setup

3.1.Flat Surfaces

Two flat surfaces made by Valley Design Corp. were used for this experiment as shown in Figure 4.

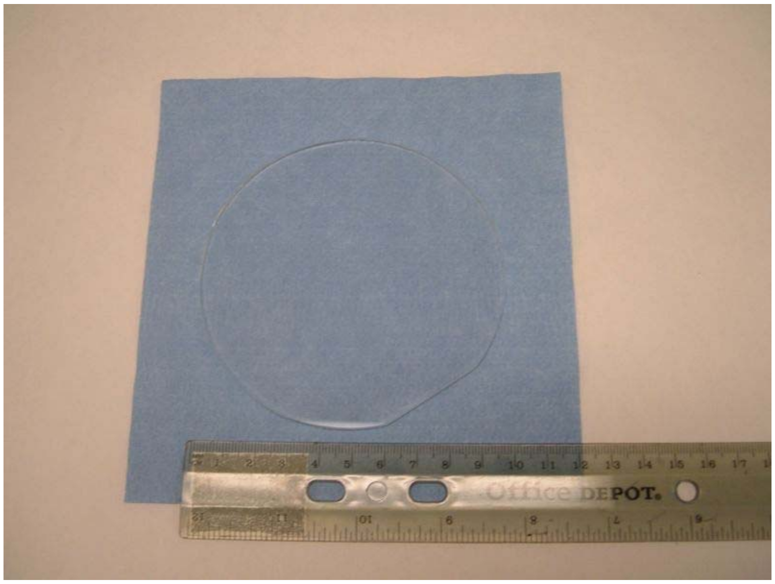


Figure 4. Flat surface

The flat surfaces were made from Borofloat, 100 mm in diameter, 2.69 mm in thickness, standard transparent finish, and 60/40 scratch/dig. The surface flatness was measured by Unilamp made by Midwest Scientific Co. as shown in Figure 5. There were about 10 fringes on the flat surfaces.

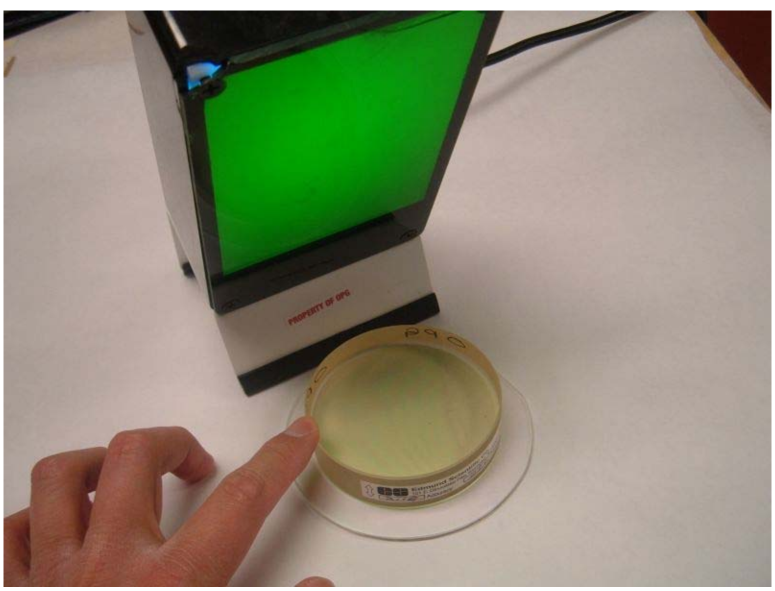


Figure 5. flatness of the flat surface

A region between two flat surfaces was sealed by an O-ring and a needle was inserted into the O-ring so that the sealed region can be evacuated. The diameter of the O-ring is 86.25 mm and thickness is 5.6 mm, and the diameter of the needle is 1.06 mm. The O-ring and the two flat surfaces were glued by RTV157 to prevent leaking from a small cavity between them as shown in Figure 6. A back surface of the flat surface measured by an interferometer was coated by #33 Liquid made by Universal Shellac & Supply company, Inc. to avoid a reflection from the back surface affecting an interferogram.

Figure 6. Flat Surface with O-ring, RTV, and needle

3.2. Requirement for Vacuum Level

By Vukobratovich page 260, Deflection caused by gravity can be calculated by using the following equation.

$$\delta_{\max} = C_D \left(\frac{\rho g}{E}\right)\left(\frac{r}{h}\right)^2 r^2 \left(1-\nu^2\right)\cos\theta \qquad \text{(Eq. 1)}$$

δ_{max} is the maximum surface deflection
C_D is the deflection constant
ρ is the material density
E is the elastic modulus
r is the radius of the evacuated area
h is the thickness of the flat surface
θ is the angle between the optical axis and local vertical
ν is the Poisson's ratio

Since Pressure (P) = Force / Area = ρgh, the (Eq. 1) can be described as the following.

$$\delta_{\max}(P) = C_D \left(\frac{P}{E}\right)\frac{r^4}{h^3}\left(1-\nu^2\right)\cos\theta \qquad \text{(Eq. 2)}$$

By Vukobratovich page 261, CD = 0.828 (Edge simply supported) for the O-ring. E = 64 GPa and ν = 0.2 for Borofloat glass, r = 43.125 mm, h = 2.69 mm, and θ = 0. When P = 1000 Pa, the (Eq. 2) becomes the following.

$$\delta_{\max}\left(P\right)=0.828\left(\frac{1000}{64\times10^{9}}\right)\frac{0.043125^{4}}{0.00269^{3}}\left(1-0.2^{2}\right)=2.21\,um \qquad \text{(Eq. 3)}$$

2.21 um is enough to obtain reasonable accuracy by an interferometer. Then the target of vacuum level for the system was 1000 Pa.

3.3. Vacuum System

Schematic of the vacuum system is shown in Figure 7 and the actual system is shown in Figure 8. The needle inserted into the O-ring connects to the vacuum system consisted of a vacuum pump, a reservoir, a leak valve, and a pressure gage.

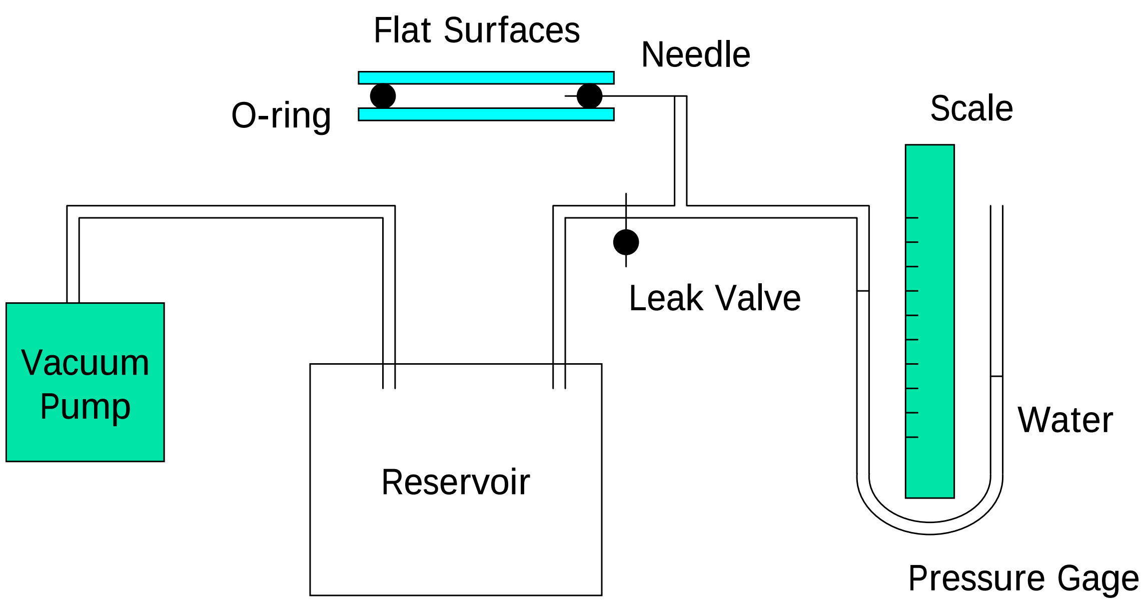


Figure 7. The vacuum system

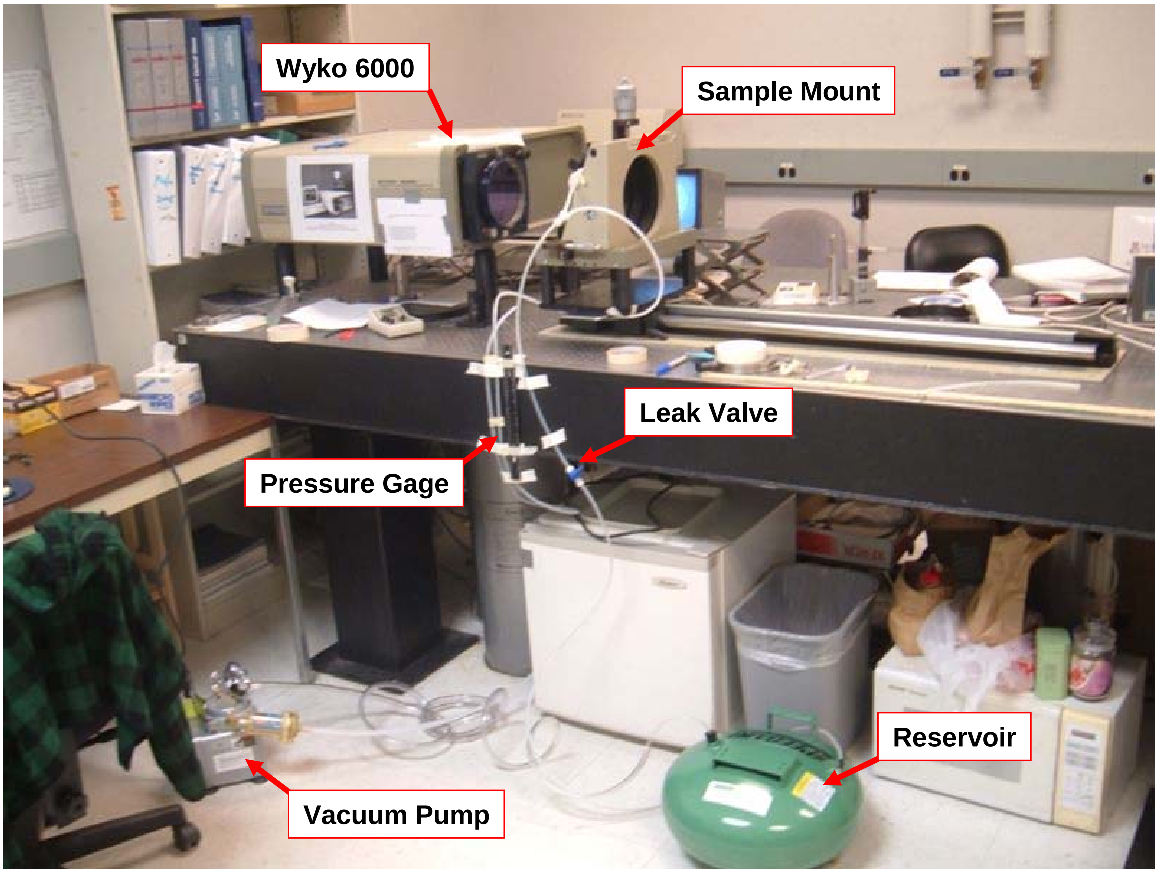


Figure 8. The actual system

The pressure gage consists of just a tube filled by water and a scale as shown in Figure 9 so that a sensitive vacuum level measurement can be achieved in low cost.

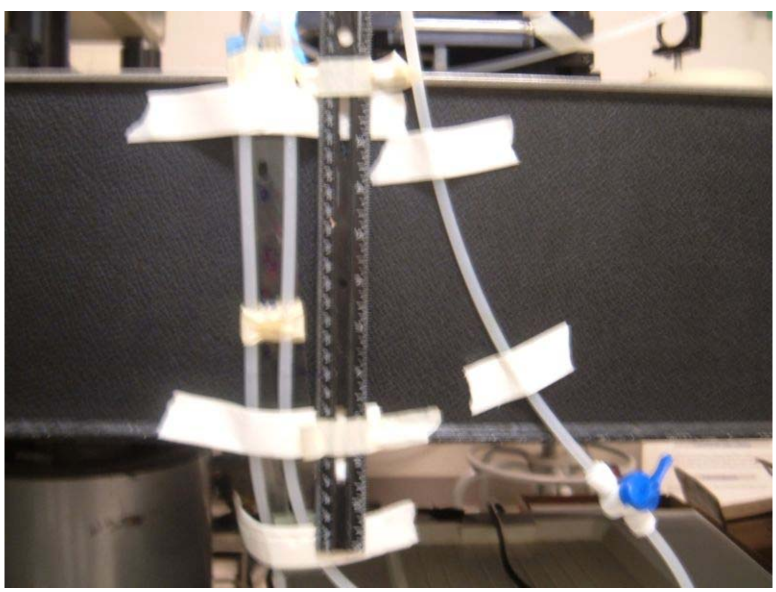


Figure 9. Pressure gage

In this experiment, a sensitivity required to the pressure gage was relatively tight because a little pressure change can affect on an interferogram easily. Also, the pressure should be measured around air pressure. If the pressure to be measured was around ultra high vacuum level, there would be a very sensitive gage like B-A gage. But, in this case, the gage being able to measure around air pressure sensitively was required. Then, a water height gage was chosen. Since 1 atmosphere is equivalent to 10.3 m in water height, the height of 101.7 mm is changed in 1000 Pa.

The reservoir shown in Figure 10 was used to avoid immersing the vacuum pump from a miss operation of the leak valve. When an operator makes the leak valve open more than what the operator expects, the water of the pressure gage goes into the reservoir not into the vacuum pump.

Figure 10. Reservoir

3.4. Interferometer

The flat surfaces were set in front of Wyko 6000 interferometer as shown in Figure 11.

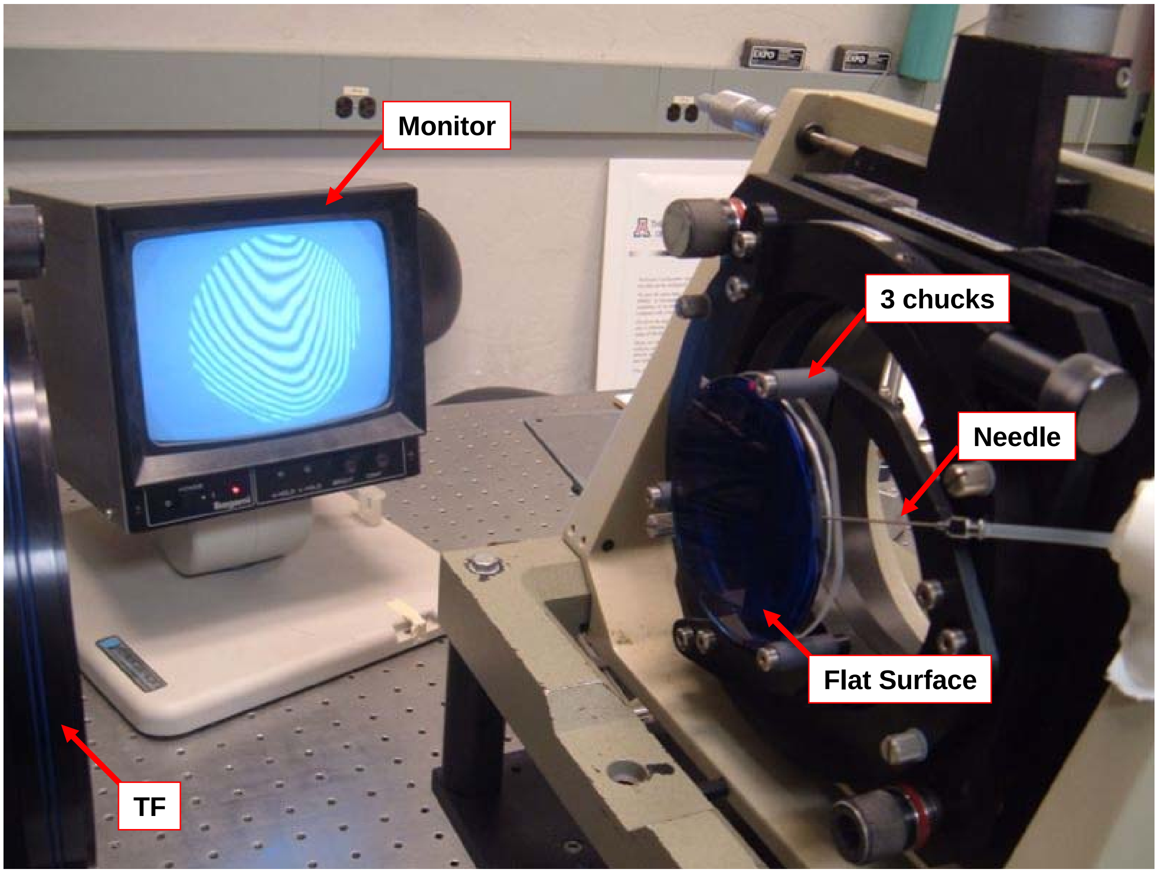


Figure 11. Flat surface mount

Three chucks held the flat surfaces about 300mm apart from Transmission Flat (TF). TF was aligned perpendicular to a collimated beam from the Wyko 6000, and then also the flat surfaces were aligned as same as TF. Focus, magnification, and intensity of Wyko 6000 were adjusted for the flat surfaces. When the flat surfaces are evacuated, the needle could move easily. To avoid the needle movement, a tube connecting the needle was fixed to the mount shown in Figure 11.

The vacuum pump was vibrationally isolated from an optical table. Then an interferogram was not affected by vibration caused by the vacuum pump.

4. Results

4.1. Experiments

Maximum deflection talked in Section 3.2 strongly depends on where an origin is. In this experiment, since the O-ring itself must be squeezed by vacuum, then it is not smart idea to use maximum deflection to evaluate deflection amount. Instead of using maximum deflection, using Zernike terms is much smarter method to evaluate deflection effects.

Zernike 1st (Z1: Piston), Zernike 2nd (Z2: Tilt X), and Zernike 3rd (Z3: Tilt Y) terms were initially removed from all experimental data because these terms can be changed depending on how much misalignment the system has. Also, changes of Z1 to Z3 when the flat surfaces were evacuated should be ignored because all non-uniformity affair, such as the O-ring, adhesive, and glass surfaces, can affect Z1 to Z3. If the system was perfect like in simulation, only symmetry terms, such as Z4, Z11, and higher order spherical terms, would be appeared in surface deflection data. But the actual system is not perfect, then, asymmetry terms, such as Z5 and Z6 (Astigmatism) were came up.

Figure 12 shows surface deflection data of the flat surfaces.

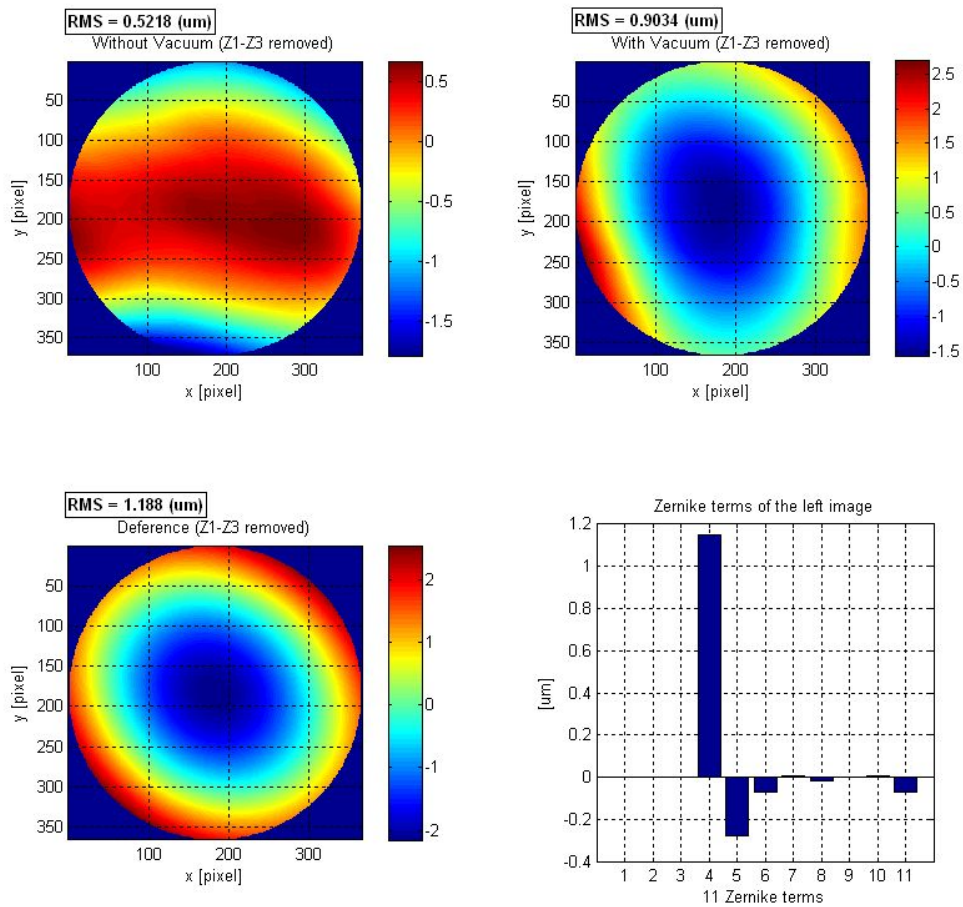


Figure 12. Surface deflection data when P = 2006 [Pa]

The upper left shows a surface data without evacuation, which means 0 [Pa]. The upper right shows a surface data with 2006 [Pa] evacuation. The left below shows a difference between the data without evacuation and with evacuation. And the right below shows how much Zernike terms the difference data has. Z1, Z2, and Z3 are removed from all deflection data. And, surface deflection data of 0 [Pa] and 2006 [Pa] are averaged by 3 data taken at the same pressure.

As the Figure 12 shows, the 1st dominant Zernike term is Z4 (power term) and 2nd dominant term is astigmatism. The astigmatism was caused by non-uniformity effect. Details are discussed in Section 5.

4.2. Simulations

Simulation for the flat surfaces deflection was implemented by SolidWorks. Figure 13 shows a simulation result when the pressure is equal to 2006 [Pa].

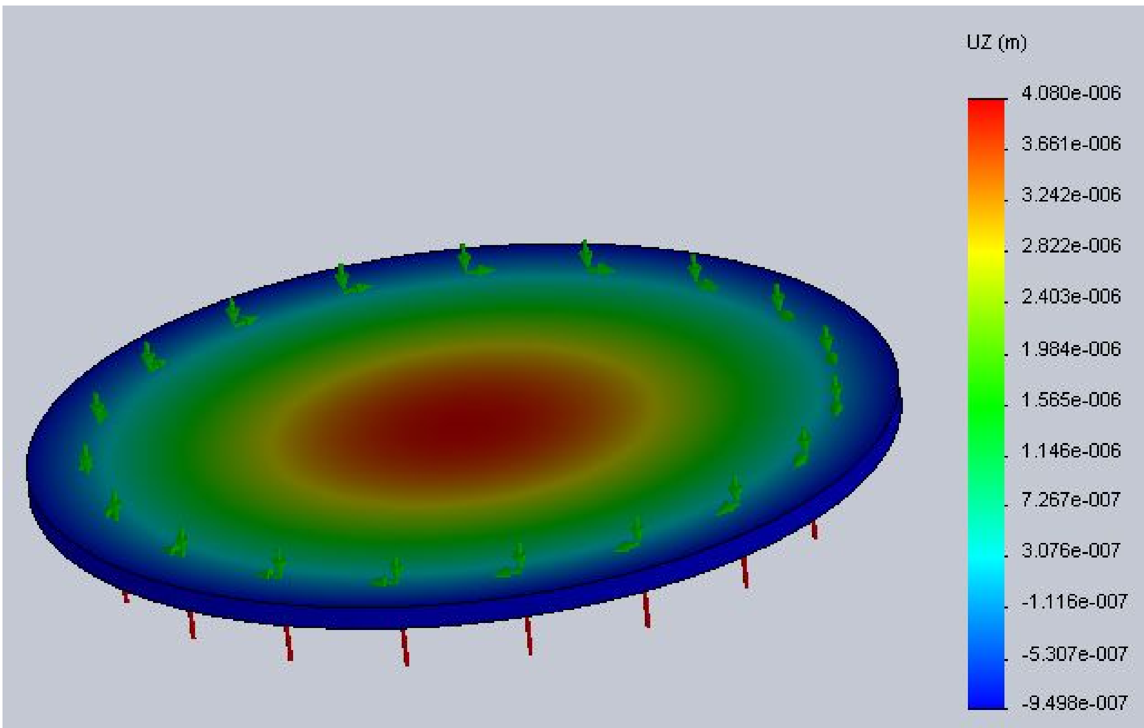


Figure 13. SolidWorks simulation result

This model shows only one flat surface sealed upside. The air pressure shown in Red arrow pushes the flat surface from the bottom. The diameter of fixture points shown in Green arrow is same as the diameter of the O-ring of 86.25 [mm]. The size of mesh is 2 [mm] in global and 0.1 [mm] in tolerance, which can provide an enough saturation of under 0.05 % change of maximum deflection. The most noteworthy topic here is how the flat surface should be restrained. As Figure 13 shows, the restraints existing along the O-ring just constrain tangential and perpendicular directions, do not constrain rotation about the O-ring. If the rotation about the O-ring is constrained, the deflection caused by vacuum becomes smaller than the actual deflection because the restraints about the rotation make the flat surface harder. Since the actual O-ring does not constrain the rotation about the O-ring, then the restraints in simulation should imitate the actual restraints.

The surface deflection results by SolidWorks are transferred to "SurfaceAnalyzerV0.2" developed by Won Hyun Park. This software can calculate Zernike terms of the deflected surface. Then, the simulation data can be compared with the experimental data via Zernike terms. The simulation data at several pressure levels would be discussed in Section 5.

5. Discussion

Figure 14 shows the relationship between pressure and Zernike 4th terms (Z4) for both the experimental data and simulation data for the flat surfaces evacuation.

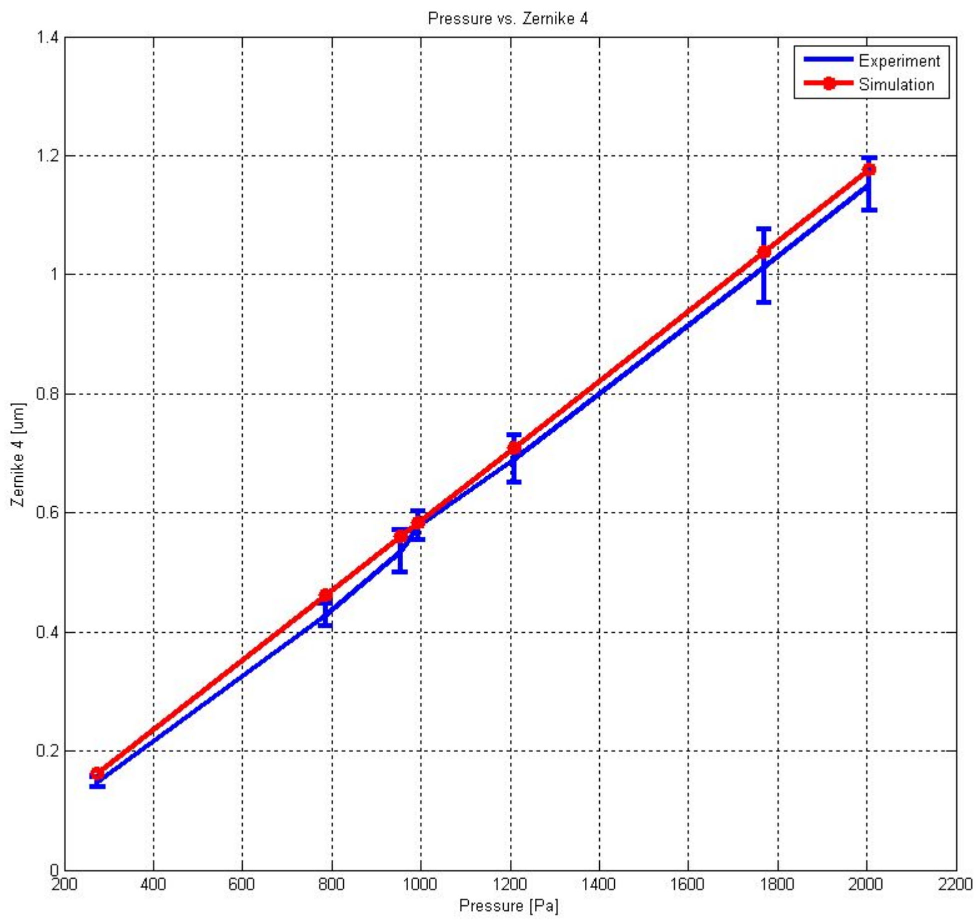


Figure 14. Pressure vs. Zernike 4th term

The experimental data is shown in blue line with error bars and simulation data is shown in red line. The relationship between pressure and Z4 is linear. In experimental data, the blue line connects the average points calculated by 3 same pressure data. Also, each data has error bars calculated by 3 same pressure data. Figure 14 shows an excellent correspondence between experimental data and simulation data in this region. The maximum difference between experiment and simulation is 9.6 [%] in 275 [Pa] calculated by the following equation.

$$Difference\,[\%] = \left|\frac{Experiment - Simulation}{Experiment}\right| \times 100 \qquad \text{(Eq. 4)}$$

The minimum difference is 0.8 [%] in 993 [Pa] calculated by (Eq. 4). All simulated Z4 are within experimental error bars or close to error bars.

The reason why the maximum pressure was 2006 [Pa] is the limitation of the interferometer. An increase of tilt fringes makes unwrapping of fringes difficult. Because of non-uniformity effect, tilt fringes came up more and more when the pressure became high. Even if Wyko 6000 software could unwrap the fringe data with many tilt fringes, an uncertainty of data would become worse. Though 2200 [Pa] simulated in LSST model cannot be measured in the flat surface experiment, 2200 [Pa] simulation seems to be correspondent with experiment because the difference between simulation and experiment does not depend on pressure.

The other Zernike 5th (Z5) and 11th (Z11) terms are shown in Figure 15.

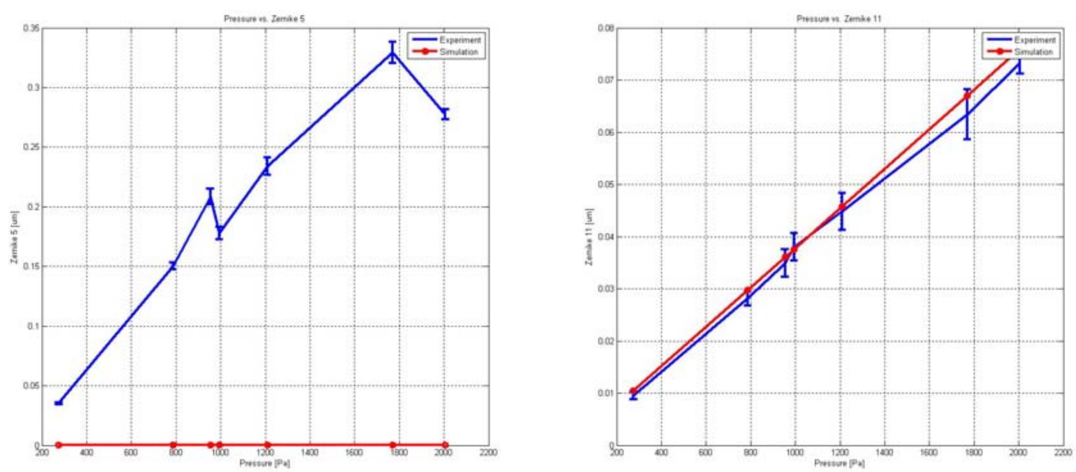


Figure 15. Z5 and Z11

The left graph shows Z5 case and the right graph shows Z11 case. As same as Figure 14, the experimental data is shown in blue line with error bars and simulation data is shown in red line. Since the amount of Z5 was bigger than other Zernike terms except for Z4, then it was picked up. The other Zernike terms are shown in Appendix. In Z5 graph, simulation data are zero over any pressure, because the model in simulation is fully perfect not to consider any non-uniformity. Z5 is arisen by non-uniformity effect as listed in Section 4.1. Since Zernike terms are orthonormal, Z5 or other non-uniformity terms do not affect on symmetry terms like Z4 or Z11. Astigmatism can be seen in substantial measurements of lens shapes, because Z4 or Z5 is the easiest deformation mode.

In the Z11 case, all the simulation data are within experimental error bars or close to error bars as same as the case of Z4. The maximum difference between experiment and simulation is 9.9 [%] in 275 [Pa], and the minimum difference is 1.1 [%] in 993 [Pa] calculated by (Eq. 4). These results are also same as the case of Z4. E. Everhart and G. Lemaitre shows an evacuated plate called Schmidt plate has Z4 and Z11 terms[2][3].

The reason why there is difference between simulation and experimental data is the error in estimation of evaluated area, which is equal to the diameter used by Zernike terms calculation. Z4 is not strongly affected by the evaluated area because Z4 has only ρ squared term. However, since Z11 has two terms of biquadratic and quadratic ρ, then Z11 is sensitive to the evaluated area. Therefore, the difference of the evaluated area affects on the difference between simulation and experimental data.

6. Conclusion

The vacuum experiment using the evacuated flat surfaces of 100 [mm] in diameter and 2.69 mm in thickness was implemented to verify simulation data correspond with experimental data. The relationship between pressure and deflection described by Zernike 4th and 11th terms was obtained by the experiment. The maximum difference between experimental data and simulation data was 9.6 [%] in Zernike 4th term and 9.9 [%] in Zernike 11th term at 275 [Pa], and the minimum difference was 0.8 [%] in Zernike 4th term and 1.1 [%] in Zernike 11th term at 993 [Pa].
Therefore, it was validated that simulation about deflection caused by vacuum well corresponded with experimental data.

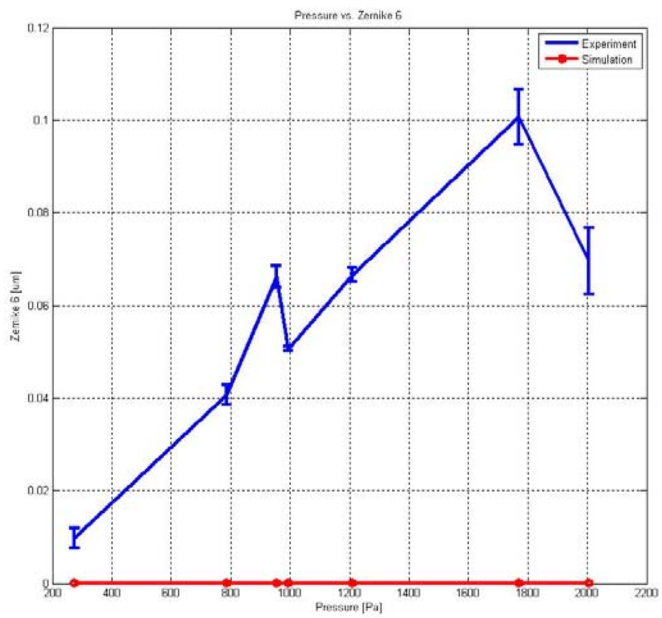
7. Acknowledgments

The author wish to express my appreciation to Professor Robert E. Parks, Professor James H. Burge, Professor Matthew B. Dubin for their constructive advices, and Won Hyun Park for his software of SurfaceAnalyzerV0.2.

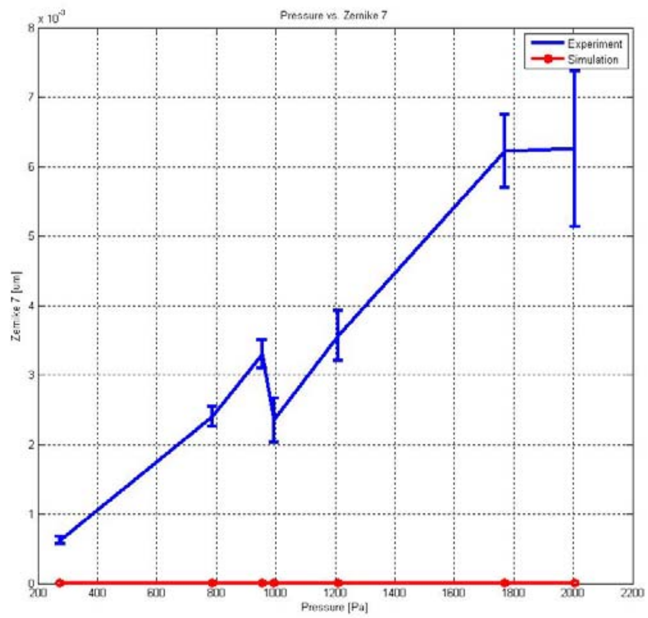
8. References

[1] M. B. Dubin, et al., “Fizeau interferometer with spherical reference and CGH correction for measuring large convex aspheres”, Proceedings of the SPIE, Volume 7426 (2009)
[2] E. Dverhart, “Making Corrector Plates by Schmidt’s Vacuum Method”, Applied Optics, Vol. 5 Issue 5, pp. 713-715 (1966)
[3] G. Lemaitre, “New Procedure for Making Schmidt Corrector Plates”, Applied Optics, Vol. 11 Issue 7, pp. 1630-1636 (1972)

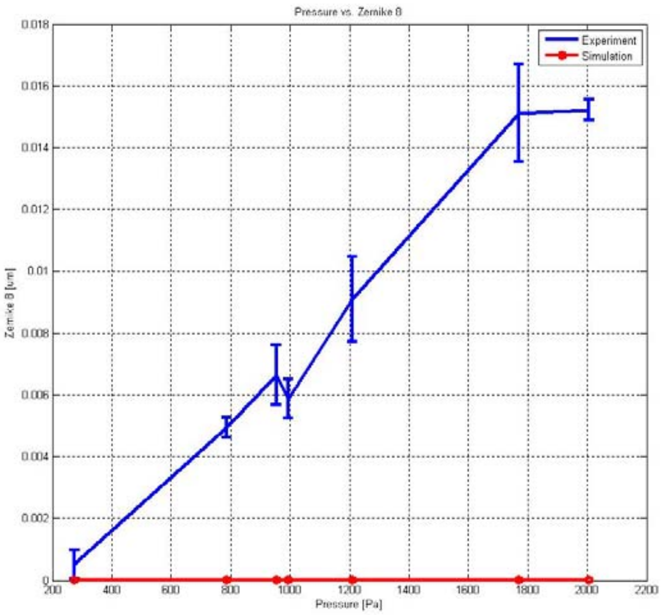
9. Appendix

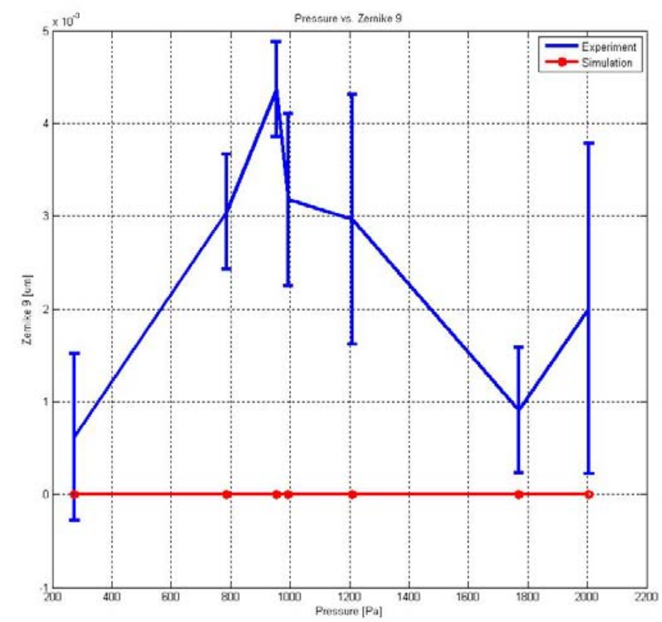


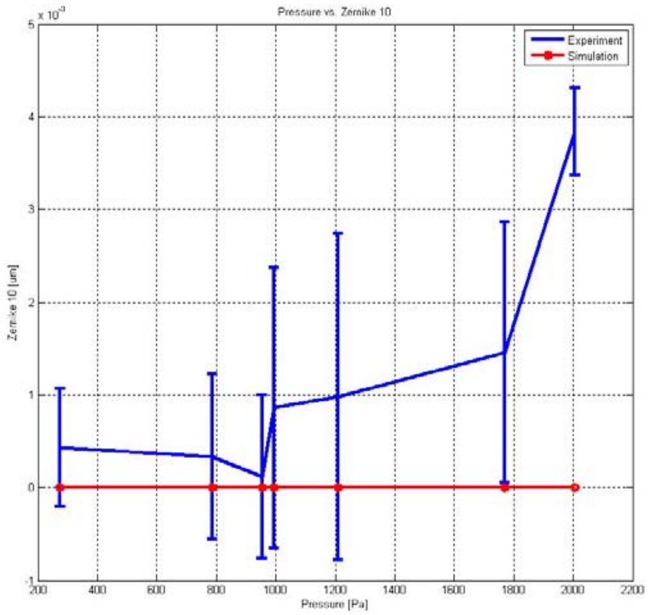
Pressure vs. Zernike 6
Experiment
Simulation
Zernike 6 [um]
Pressure [Pa]
0.12
0.1
0.08
0.06
0.04
0.02
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200



Pressure vs. Zernike 7
x 10^-3
Experiment
Simulation
Zernike 7 [um]
Pressure [Pa]
8
7
6
5
4
3
2
1
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200


Pressure vs. Zernike 8
Experiment
Simulation
Zernike 8 [um]
Pressure [Pa]
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200


Pressure vs. Zernike 9
Experiment
Simulation
Zernike 9 [um]
Pressure [Pa]
x 10^-3
5
4
3
2
1
0
-1
200
400
600
800
1000
1200
1400
1600
1800
2000
2200


Pressure vs. Zernike 10
x 10^-3
Experiment
Simulation
Zernike 10 [um]
Pressure [Pa]
5
4
3
2
1
0
-1
200
400
600
800
1000
1200
1400
1600
1800
2000
2200