Tolerance analysis using Zemax, the case for the small optics.

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Abstract
A systematic procedure to perform tolerance analysis of the small optics has presented. To implement this of this procedure, a typical cell phone camera lens has been chosen to evaluate performance degradation of the optical system. This outline could provide a starting point to understand small optics tolerancing and the instructions to use Zemax as a design and tolerancing tool.

1. Introduction

A few obvious trends in current consumer electronic devices are small and compact size but performing high with very reasonable price. Optics inside those products are not the exception. It is getting thinner but has to be performing much better than before with higher pixel resolution. As a result of those tight requirements, the tolerances are very tight and challenging. In this article, a systematic procedure for the tolerance analysis by Zemax has presented. The details about the design of three plastic lens elements are not covered in this article.

2. Procedure to perform tolerance analysis

The basic outline of the optical tolerancing procedure has presented in Fig. 1). In this analysis, as small cell phone camera lenses don't have complicated mechanical focusing features, only those blue-boxed tasks are completed. Pink boxed tasks are done but will not be discussed in this article.

Fig. 1) Basic outline of the tolerancing(1)

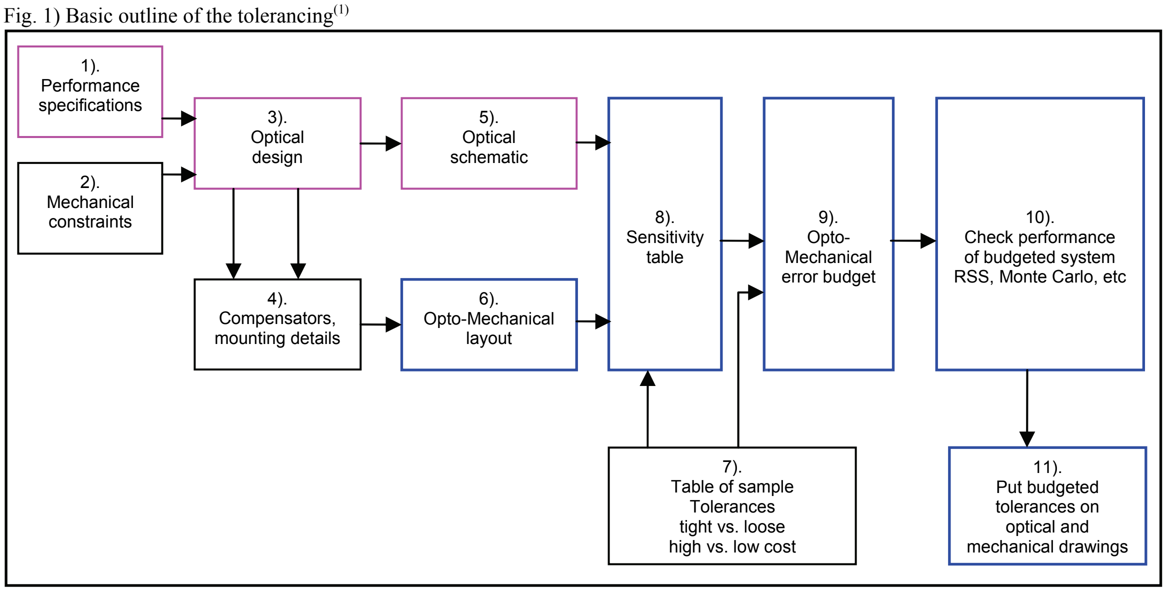

Table 1) is specification of required lens. Its F# is 2.8, pixel size is 5.6µm, and required resolution at center is 125lp/mm. This is typical specification of fixed focus VGA cell phone camera lens. As a merit function of the sensitivity analysis, 20% MTF drop at 45 lp/mm frequency is used.

Table 1) Design specification

Specification item	Required performance
Field of view	60 degrees
F#	2.8
Number of lens elements	3 plastic lenses
Pixel size	5.6 µm
Image sensor size	3.58mm x 2.69mm
Resolution	125lp/mm @center

3. Optical layout for cell phone camera

Fig. 2) is optical layout of cell phone camera. It has three aspheric plastic lenses, both sides are aspheres and there are two aperture stops between surface 3 and 6. As shown in Fig. 3), the materials are Zeonex E48R and Polycarbonate. Their indices are around 1.45~1.5. It is very clear and stable compare to conventional optical plastic. The total length from first surface to image plane is about 5.3mm and the lens diameters are from 2.6mm to 4.6mm.

Fig. 2) Optical layout with 3 plastic aspheric lenses

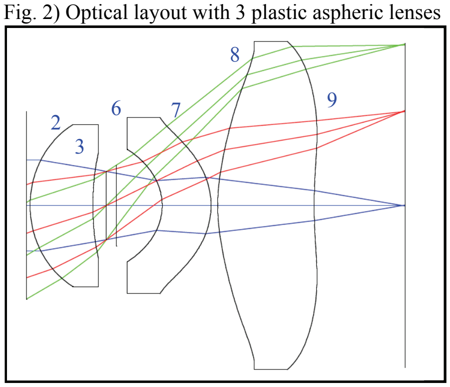

Fig. 3) Lens data in Zemax

Lens Data Editor: Config 1/10

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Surf	:Type	Comment	Radius		Thickness		Glass		Semi-Diameter	
OBJ	Standard		Infinity		600.000000				354.008504	
1	Standard		Infinity		0.050000				1.318680	U
2*	Even Asphere	Lens1 S1	1.451163		0.882192		E48R		1.140000	U
3*	Even Asphere	Lens1 S2	3.875008		0.190915				0.740000	U
STO*	Standard	Stop	Infinity		0.142000				0.480000	U
5	Standard		Infinity		0.642060				0.571108	U
6*	Even Asphere	Lens2 S1	-0.766905	V	0.685986		POLYCARB		0.790000	U
7*	Even Asphere		-1.084190	V	0.095000				1.240000	U
8*	Even Asphere	Lens3 S1	2.688664		1.354211		E48R		2.180000	U
9*	Even Asphere		6.001852		1.276980				2.310000	U
IMA	Standard		Infinity		-				2.276326	

4. Optomechanical layout

Fig. 4) is optomechanical layout. Due to dimensional restriction and cost reduction requirement, these are manufactured from plastic injection molding process. All lenses have their own individual mount so that the flange surfaces are stacked together with respect to the bore surface of the barrel. A plastic injection molded aperture stop is located between lens1 and lens2. Lens3 will be located after lens2. Retainer will be glued to the barrel to maintain lens assembly and survived from the shock and keep all required tolerance remained.

Fig. 4) Optomechanical layout

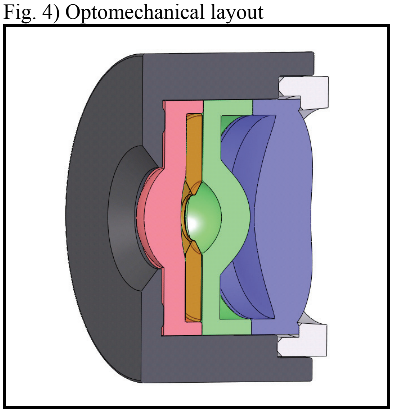
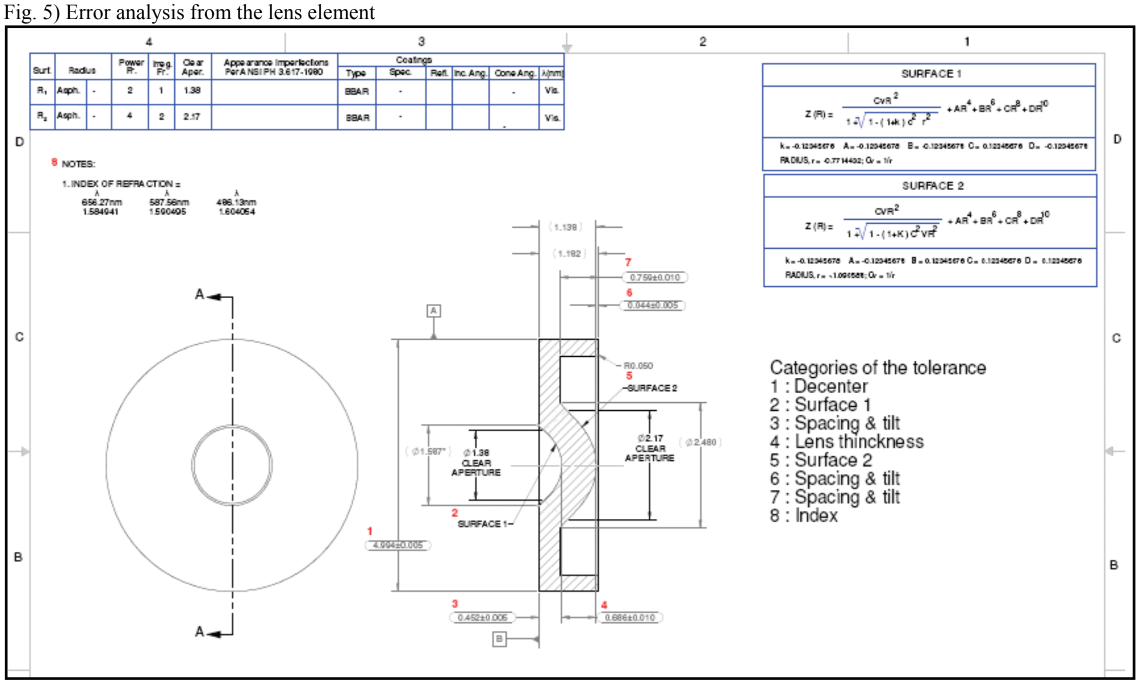


Fig. 5) is the part of the drawing that has all the necessary tolerances are specified. At the top left corner, surface power and irregularity tolerances are specified and the note below is the index of refraction. Aspheric equation and their coefficients have described in the box at the top right corner. On the lens drawing, center thickness, element tilt, element decenter, and element spacing tolerances are specified. All these specific numbers are come from tolerance analysis.

Fig. 5) Error analysis from the lens element



5. Sensitivity table and error budget

Fig. 6 and 7 are input data to execute tolerance analysis from Zemax. Perturbed amounts are 1 fringe for radius of each surface(power), 0.01mm for thickness, 0.05 degree for surface tilt, 0.001 for index change, 0.05 degree for element tilt, and 0.010mm for element decenter. Zemax allows us to tolerate surface irregularity by assigning tolerance operand TEZI which is simulating surface by adjusting Zernike coefficient. 0.00005mm is used as RMS surface irregularity.

Fig. 6) Tolerance input to the Zemax

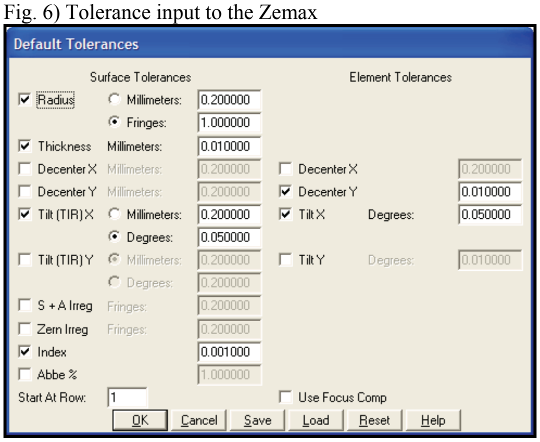
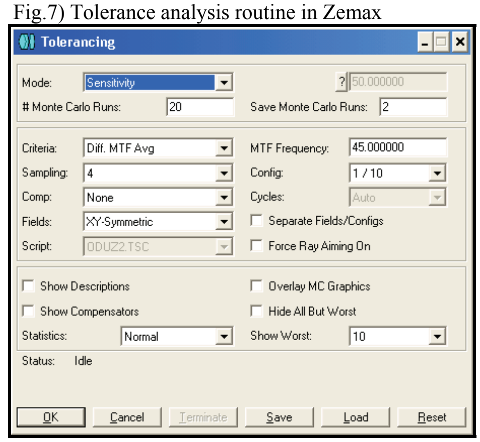


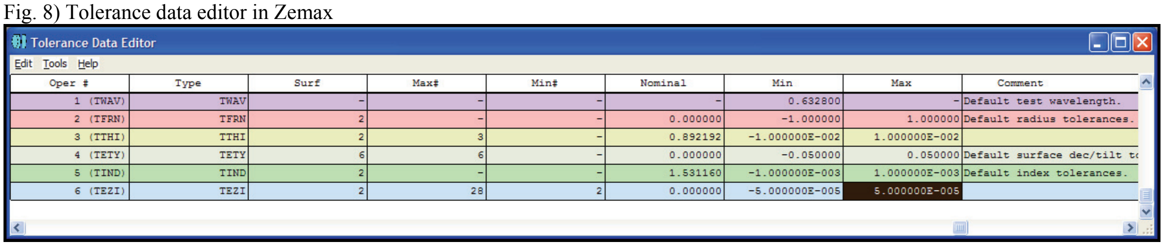
Fig.7) Tolerance analysis routine in Zemax



After completed to define tolerances, the Zemax will generate tolerance table in Fig. 8). Then we can run tolerance analysis routine. From the command box shown in Fig. 7), we can calculate sensitivity to the given merit function.

As a merit function to evaluate performance degradation, percentile MTF drop at Ny/2 has selected. Because resolution and contrast is one of the main category to evaluate image quality of the camera. Since this system uses 5.6µm pixel for the image sensor, the Nyquist frequency is 89lp/mm and Ny/2 is 45lp/mm.

Fig. 8) Tolerance data editor in Zemax



Tolerance Data Editor

Edit Tools Help

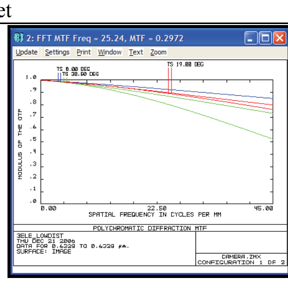
Oper #	Type	Surf	Max#	Min#	Nominal	Min	Max	Comment
1 (TWAV)	TWAV	-	-	-	-	0.632800	-	Default test wavelength.
2 (TFRN)	TFRN	2	-	-	0.000000	-1.000000	1.000000	Default radius tolerances.
3 (TTHI)	TTHI	2	3	-	0.892192	-1.000000E-002	1.000000E-002	
4 (TETY)	TETY	6	6	-	0.000000	-0.050000	0.050000	Default surface dec/tilt t
5 (TIND)	TIND	2	-	-	1.531160	-1.000000E-003	1.000000E-003	Default index tolerances.
6 (TEZI)	TEZI	2	28	2	0.000000	-5.000000E-005	5.000000E-005	

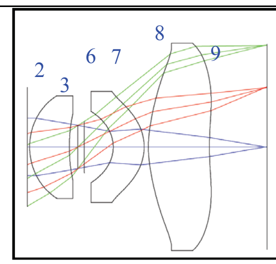
Table 2 is the result sensitivity table and error budget. Presented percentile MTF drop is from the 0 degree field at 0.632µm wave. Optical schematic has been attached on top the table to identify effects easily.
From the analysis result, we can have following results:

- Lens 1 and following space : The dominant variables are index change and power tolerance for the surface 2 and surface 3 are second dominant. Thickness and decenter tolerance is not as sensitive as previous three parameters. The effect of surface irregularity, lens1 and 2 spacing, and element tilt are almost negligible. Surface wedge is negligible through the entire system. So it doesn't need to be taken into consideration for this system.
- Lens 2 and following space : Dominant tolerances are power of two surface and spacing between lens 2 and lens 3. Thickness is next dominant one and after then other tolerances are all insensitive. Lens 2 is the least sensitive element.
- Lens 3 and space between image plane : Center thickness and space tolerance between lens and image plane are most dominant variables. Power tolerance of the surface 8 is second most sensitive tolerance than others. The rest of the other tolerances are quite forgiving compare to other lenses.

The RSS results have been calculated after each lens error and total RSS has calculated based on the error of each lens. The total RSS of system degradation due to tolerated error is 17.7% of MTF drop. Therefore the design specification less then 20% at Ny/2 is achieved.

Table 2. Sensitivity table and error budget





Nominal MTF @45lp/mm : 0.851

1. Surface Element	2.Parameters and comment	3. Nominal value	4. Perturbation	5. MTF drop	6. Sensitivity	7. Tolerances	8. Total % MTF drop
Lens1	Index of refraction	1.5312	0.0010	0.0550	55.03	0.00100	5.50
2-3	Thickness(mm)	0.8822	0.0100	0.0283	2.83	0.01000	2.83
	Tilt(deg)	0.0000	0.0500	0.0001	0.00	0.10000	0.02
	Decenter(mm)	0.0000	0.0100	0.0131	1.31	0.02000	2.62
2	Radius(mm)	1.3941	0.0011	0.0333	30.25	0.00220	6.66
2	Irr(mm)		0.0001	0.0001	2.80	0.00005	0.01
2	~~Wedge(deg)~~		~~0.0500~~	~~0.0002~~	~~0.00~~	~~0.10000~~	~~0.04~~
3	Radius(mm)	2.3987	0.0066	0.0410	6.20	0.01320	8.19
3	Irr(mm)		0.0001	0.0035	69.36	0.00005	0.35
3	~~Wedge(deg)~~		~~0.0500~~	~~0.0000~~	~~0.00~~	~~0.10000~~	~~0.00~~
	L1-L2 Spacing	0.9750	0.0100	0.0006	0.06	0.01000	0.06

	RSS of all Lens1 error			0.0824			12.52
Lens2	Index of refraction	1.2855	0.0010	0.0045	4.52	0.00100	0.45
6-7	Thickness(mm)	0.6690	0.0100	0.0174	1.74	0.01000	1.74
	Tilt(deg)	0.0000	0.0500	0.0001	0.00	0.10000	0.02
	Decenter(mm)	0.0000	0.0100	0.0029	0.29	0.02000	0.58
6	Radius(mm)	0.9225	0.0009	0.0182	21.44	0.00170	3.65
6	Irr(mm)		0.0001	0.0046	91.50	0.00005	0.46
6	Wedge(deg)		0.0500	0.0003	0.01	0.10000	0.06
7	Radius(mm)	1.4327	0.0008	0.0086	10.23	0.00336	3.44
7	Irr(mm)		0.0001	0.0042	83.12	0.00010	0.83
7	~~Wedge(deg)~~		~~0.0500~~	~~0.0002~~	~~0.00~~	~~0.10000~~	~~0.05~~
	L2-L3 Spacing	0.0950	0.0100	0.0348	3.48	0.01500	5.22
	RSS of all Lens2 error			0.0624			7.54
Lens3	Index of refraction	1.5312	0.0010	0.0056	5.56	0.00100	0.56
8-9	Thickness(mm)	1.2940	0.0100	0.0582	5.82	0.01000	5.82
	Tilt(deg)	0.0000	0.0500	0.0000	0.00	0.10000	0.00
	Decenter(mm)	0.0000	0.0100	0.0008	0.08	0.02000	0.16
8	Radius(mm)	4.8695	0.0032	0.0021	0.64	0.01595	1.03
8	Irr(mm)		0.0001	0.0015	29.99	0.00015	0.45
8	~~Wedge(deg)~~		~~0.0500~~	~~0.0000~~	~~0.00~~	~~0.10000~~	~~0.00~~
9	Radius(mm)	8.2474	0.0085	0.0007	0.09	0.04250	0.36
9	Irr(mm)		0.0001	0.0004	4.37	0.00030	0.13
9	~~Wedge(deg)~~		~~0.0500~~	~~0.0000~~	~~0.00~~	~~0.10000~~	~~0.00~~
	L3-Image Spacing (mm)	1.2170	0.0100	0.0532	5.32	0.01500	7.99
	RSS of all Lens3 error			0.0789			9.97
	Total RSS			**0.1302**			**17.69%**

6. Conclusion

After completing tolerance analysis for the cell phone camera lens using Zemax, we have following conclusions,

a. From the given optical design, optomechanical layout has been presented.
b. Actual drawing with tolerance for the lens fabrication has been presented.
c. Dominant errors and negligible errors have been clarified after tolerance analysis. Lens thickness, space between lens and power of each surfaces are dominant factors to affect performance.
d. Over all tolerance guide line has been met with 17.7% MTF drop at 45lp/mm

7. References

(1) Robert H. Ginsberg, "Outline of tolerancing (from performance specification to tolerance drawing)", Optical Engineering, March/April 1981, Vol. 20, No. 2, pp. 175-180

(2) Zemax manual and Zemax knowledge base website.