AN OPTICAL SYSTEM DESIGN METHOD FROM OFF-THE-SHELF OPTICAL COMPONENT

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Abstract

Numerous number off-the-shelf optical lenses and lens components are available for use in the design of new optical systems. But there isn't a clear methodology on how effective there are in a real optical instrument. The reason for this is that the most common way to use off-the-shelf optical components is in metrology test stands. There is no volume restriction and off-the-shelf lenses work with low numerical apertures, field angles, and small field sizes. For this working condition, image quality is good due to small aberration. The other case is if those components will be used in real manufactured optical systems. Here lens effectiveness plays a more important role and an optimal optical system structure need to be found. In this article new method of evaluation of any lens optical components will be introduced. In other words, this method will provide a measure of the effectiveness of lens components. This method was developed for single lenses, cemented doublets, and triplets. For this approach, the new optical parameter which simultaneously includes the glass refraction index and Abbe number will be proposed. The combination of refractive index and Abbe number allow evaluation level of mono and chromatic lens aberration thru one parameter.

Comparisons of wave aberration (optical path difference-OPD) for different off-the-shelf lenses and lens components will be present for all cases. In conclusion, OPD results for various optical lenses and components will be discussed.

Introduction

Using off-the-shelf optical components in a custom optical system possesses a number of advantages: short delivery time, low cost, quick replaceability, and unbounded delivery. Nevertheless, off-the-shelf optics seldom use as a part of custom optical design. The main topic of this article is to provide effectiveness criteria for off-the-shelf optics lens components. The effectiveness of each component is based on the level of lens residual aberration and as a result of image quality prediction. For this purpose, off-the-shelf optical components with the same first-order optical parameters (focal length, number of lenses, numerical aperture, etc.) but made from different glasses were evaluated. For this evaluation, a new optical parameter will be used. The value of this parameter will be defined by optical component image quality (residual aberration). The component's effectiveness will depend on the level of residual aberration. An optical component with the best parameter value has more ability for use in custom design due to smaller input in total optical system aberration. Also, in simple cases, an off-the-shelf optical component can be used separately. It is important to know how effective it is. For this case comparison of several lenses with the same optical characteristics can provide the best solution.

The method theory

The way for off-the-shelf lens effectiveness is based on glass constants evaluation. The refractive glass index and Abbe number are the two most critical glass constants. Their composition defined the important lens ability of aberration correction. The lenses with a high refractive index value (>1.75) are effective for monochromatic aberrations correction and lenses with a high Abbe number (>80) can be used for the correction of chromatic aberrations. The proposed lens parameter comprised both glass constants. This parameter (K) is defined by formula (1).

$$\mathbf{K=n_{x}v;\ (1)}$$

Where **n** is the glass refractive index and **v** is the Abbe number. For a single lens, **K** is thoroughly defined by formula (1). The cemented glass components (doublets) which consist of 2 lenses will describe by two different K parameters. One for crown glass with positive optical power and the other for flint glass with negative optical power. The cemented doublet parameter (Kdb) defined next formula (2)

$$\mathrm{Kdb}=\frac{Klp}{Knl};\ (2)$$

Where **Kpl** is the K parameter for a lens with positive power, **Knl** is the K parameter for a lens with negative power. The reason why cemented doublet parameter was defined and how it was expressed in (2) is next: if both doublet lenses were made from the same glass **Kdb= 1**, this means there is no difference between doublet and singlet lenses. In this case, the doublet effectiveness parameter will be the equivalent K parameter of a single lens. The cemented triplet lens component is a specific case. It will be considered as two cemented doublets, where two lenses are made from the same glass. The total number of different glasses equals three, but we can operate with two different doublet lenses. The cemented triplet lens component K parameter will be defined by the next expression (3)

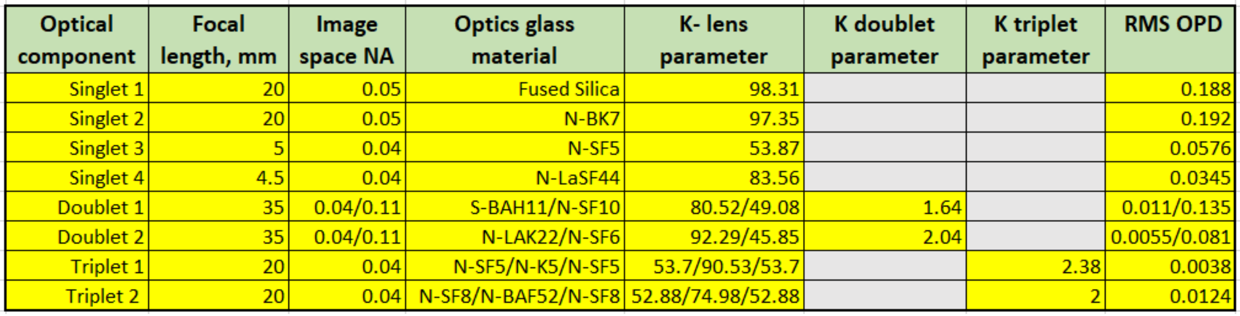
$$\mathrm{Ktr}=\sqrt{Kdb_1{}^2+Kdb_2{}^2}\quad (3)$$

Where $\boldsymbol{Kdb_1}$ and $\boldsymbol{Kdb_2}$ are K doublets parameters located inside cemented triplet lens. The formula (3) represents the “Law of addition of random values”. In our case expression (3) represents cemented triplet effectiveness parameter Ktr. The effectiveness of off-the-shelf standard optical components parameters defines by formulas (1-3). Using those formulas effectiveness parameters of any optical lens components can be calculated. Also, a comparison can be made between optical components with the same optical characteristic but made from optical glasses with different optical characteristics.

Practical method implementation

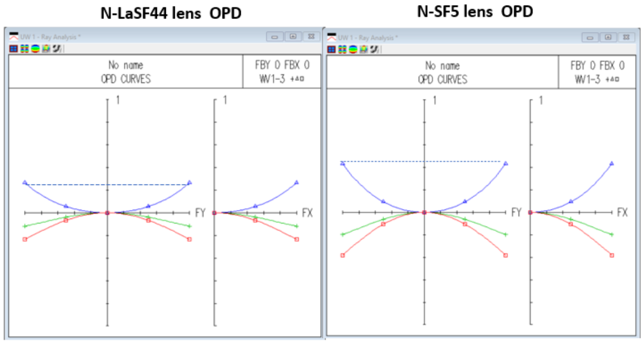
For practical methods implementation three different types, of off-the-shelf lens components were taken. It was single lenses, cemented doublets, and cemented triplets. All lens data were taken from [1,2] lens catalogs. Each group of optical components has the same first-order design data, but they were made from different glasses. Data for all types of optical components, their working condition, and calculated lens K parameters are shown in Table 1.

Table 1. Off-the-shelf optical components data



Optical component	Focal length, mm	Image space NA	Optics glass material	K- lens parameter	K doublet parameter	K triplet parameter	RMS OPD
Singlet 1	20	0.05	Fused Silica	98.31			0.188
Singlet 2	20	0.05	N-BK7	97.35			0.192
Singlet 3	5	0.04	N-SF5	53.87			0.0576
Singlet 4	4.5	0.04	N-LaSF44	83.56			0.0345
Doublet 1	35	0.04/0.11	S-BAH11/N-SF10	80.52/49.08	1.64		0.011/0.135
Doublet 2	35	0.04/0.11	N-LAK22/N-SF6	92.29/45.85	2.04		0.0055/0.081
Triplet 1	20	0.04	N-SF5/N-K5/N-SF5	53.7/90.53/53.7		2.38	0.0038
Triplet 2	20	0.04	N-SF8/N-BAF52/N-SF8	52.88/74.98/52.88		2	0.0124

The K parameters for a single lens, doublet, and triplet shown in Table 1 are defined by formulas (1), (2), and (3). In the last column root mean square (RMS) optical path difference (OPD) was received as a result of optical components aberration analyses. These results show a direct relationship between the K parameter value for any optical components and the quality of wavefront (wave aberration) in the image plane. Singlet lens 1 and Singlet lens 2 have close results for K parameter value but RMS OPD shows a small difference in wavefront aberration. This means that the suggested method has very high sensitivity. For cemented doublet lens components results were calculated for two different image space numerical aperture (NA) values. For the analysis completeness polychromatic aberration graph data be present for **F**, **C,** and **d** lines. Fig. 1 represents wave aberration plots for singlet lenses with different K parameter values. The lens with a larger K=83.56 has smaller wave aberration and better image quality. This lens with other things being equal has the advantage to be used as a single component or as a part of a complex optical system. The reason is a smaller residual aberration. In general, if any optical system includes low-aberrated lens components total lens system aberration will be also small. This idea was developed in [3] and show its effectiveness. Figure 2 demonstrate aberration plots for two different doublets. The both doublets have the same optical characteristic but they are made from different glasses. The K doublet parameters are different. Doublet with a larger K parameter value has smaller residual aberration.

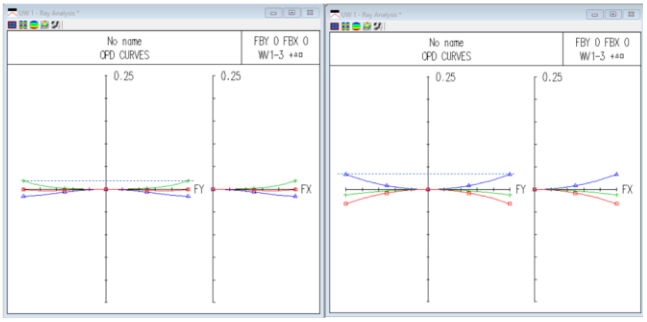

N-LaSF44 lens OPD

N-SF5 lens OPD

K=83.66

K=53.87

Fig. 1 Singlet lenses wave aberration graphs

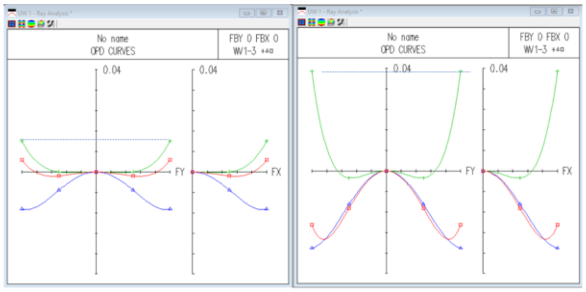


Kdb=2.04

Kdb=1.64

Fig 2. Doublet lens components wave aberration plot

There is one more type of off-the-shelf lens it’s the cemented triplet. The wave aberration for off-the-shelf cemented triplets is shown in Figure 3. As was shown in previous cases the cemented triplet lens component with a larger K parameter number has smaller wave aberration and its more favorable for use as a component in custom optical system.



Ktr=2.38

Ktr=2.0

Fig.3 Triplet lens components wave aberration plot

Thus, is possible to assert that the K parameter for any single optical lens component uniquely identifies the aberration corrective capabilities of a single optical unit.

Conclusion

Advanced lens design software gives the possibility to get the best possible lens components' shape and thickness, but choosing proper glasses is another important task that allows to dramatically improve system performance. The proposed method offers an opportunity for such kind of improvement. This method can be applied to off-the-shelf lens components. The K parameter which includes main optical glass characteristics is general for any type of optical component. Also using the K parameter for off-the-shelf lens evaluation allow the substitute of some custom lenses for lenses from optical components catalogs. This method can be used for high numerical aperture objective lens systems to find proper lens component).

REFERENCES

1. Thorlabs Product catalog. (https://www.thorlabs.com/)
2. Edmunds optics Product catalog. (https://www.edmundoptics.com/)
3. Sliusarev G.G. "Aberration and Optical design Theory", 2nd Edition, 1984, CRC Press.