Method for design an optical system from the off-the-shelf optical components

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Abstract

The numerous number off-the-shelf optical lenses and lens components are available for use in design of new optical systems. But there isn't clear methodology how effective there can be in real optical device. It should be noted that the use of standard optical elements reduces the cost of the optical device, which is especially important for mass production. Ease and speed of replacement are also important parameters for the usability of standard optical elements. That is why the extensive use of purchased optical elements in optical devices will simplify their operation and improve the convenience of maintenance. Selecting purchased optical components of an optical circuit is not an easy task and requires certain skills. The main problem is that the optical design stage is divided into two parts. The first part is the creation of an optical circuit from non-standard (custom) optical components with optical characteristics close to catalogue lenses. The second part is to adjust the optical components position to satisfied specification requirements. This process sometimes required several iterations. In order for the process of fitting distances in an optical system to be successful, it is necessary to take into account the properties of optical glasses such as refractive index and dispersion when choosing lens components, in addition to their focus lengths and geometrical dimensions. It should be noted that in the catalogs of optical components there are optical parameters of lenses, and also glass parameters of the lens. This is essential information for lens designer for substitution the custom optical element on off-the-shelf lens. Problems that arise with such a replacement are based on a limited number of standard lenses and lenses components. To get comfortable for replacement, the custom lenses components must be modified (adjust) so that optical parameters will be close enough to the parameters of the catalog lenses another word during custom lenses optimization process the lens shapes and an optical power should be fully match (in ideal case) with catalog lenses data. Method how to effectively get this match will be discussed below.

1. Introduction

The proposed method is that at the first stage it is necessary to obtain an optical system consisting of custom optical components, which would fully satisfy specification requirements.

The following stage lies in the selection of standard lenses elements with optical characteristics and geometric dimensions close by values to the data obtained. Standard (commercial) lenses should be selected from optical elements of the same type as the elements obtained as a result of the calculation, for example, glued doublets should also be replaced with glued lenses, and so on. That is, the replacement must be made with optical elements of the same type. This is done in order to change the aberrations in the optical system as little as possible during lenses replacement. It is most convenient to select optical elements for replacement using the method developed by the author [1]. This method allows to assess the degree of correction of aberration in any optical component without resorting to their calculations. To use this method, you need to know two optical characteristics: glass refractive index and Abbe number (Those glass parameters can be found in any off-the shelf lens catalog). The method was developed for singlet, cemented doublet and cemented triplet lens components. It should be noted that each optical component has residual aberrations that depend on the optical properties of the glasses of which component is made. Usually, standard optical elements are designed using optical programs to minimize aberrations, which can be achieved for particular glass or a set of glasses. Obviously, lenses having the same focal length, but made from different glasses have a different level of residual aberrations [1]. This means that if there are several lens elements with the same optical parameters in the lens catalog, the best result will be achieved if the lens component is used with the largest value of the K-parameter any off-the shelf lenses (singlets, cemented doublets and cemented triplets). The theory of this method was first presented in the article "Evaluating Off-the-Shelf Optical Components" [1] here were presented parameters of optical components, the value of which determines the degree of correctional capabilities any kind of a single optical component (single lens, glued doublet and a glued triplet). A new parameter was also introduced to the value of which is associated with residual aberrations of the optical component. It should also be mentioned that in most cases, if the individual separate lenses components of the optical system have small residual aberrations, the total aberrations of the entire system will also be small [2]. This approach allows to determine and choose best (having minimal residual aberrations) optical components and create an optical system without custom optical elements. In general, the optical schematic of the measuring (observational) device includes three parts: the objective lens (head part), the relay system and a lens block that creates an image of the object. These optical systems can be designed separately or jointly depending on the requirements of the specification. Each of these systems may include a set of lenses components or a single component (lens). Replacing these optical elements on lenses from lens catalogs allows get a number of previously mentioned benefits.

2. The Head part of an optical system

The head lens group is most important part of optical system. Usually, the head lens elements work in most hard-working conditions such as large NA (numerical aperture), long working distance and large object size. That is why this part contains the largest number of optical components. Only in the simplest cases such as low NA, short working distance and small object size the front part includes only a single lens component. Here we will consider a more general case when the front part includes two optical components. Even if you can find a single component in the catalog with necessitate focal length which is equal the head part focus length of the optical system, this does not mean that it will be suitable for replacement, due to the lack of lenses in the catalogs, with high optical characteristics, which are required for aberration correction. The most convenient front part consists of two cemented doublets Fig. 1. These doublets work as single lens block and changing air distance **d** between them allows change the focus of this lens group.

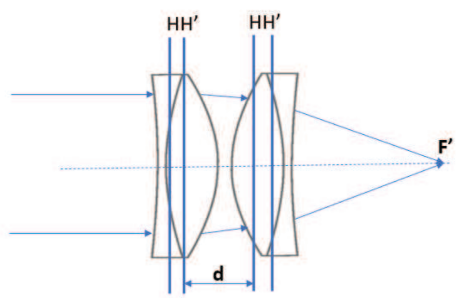

Fig. 1 Two cemented doublets lens group

The total focal distance of two cemented doublets can be defined by next formulae

$$\Phi=\varphi_1+\varphi_2-d\varphi_1\varphi_2; \quad (1)$$

Where φ_1 and φ_2 are an optical power cemented doublets and d is distance between doublets principal planes.

In a particular case, when both lens components have equal optical power formula (1) is given to mind

$$\Phi=2\varphi_1-d\varphi_1; \quad (2)$$

From formulae (1) and (2) it is clear that changing distance between lens components total optical power the doublets lens group also changed. This facilitates the selection of standard components for the optical system. Doublets tandem also allow to reach better aberration correction than single lens elements, because in and single cemented doublets in this case the aperture rays fall into optical elements at smaller angles, which allow to reduce higher-order aberrations. The simplified version of the tandem is a combination that includes cemented doublet and single lens.

3. Subsequent optical system part

The subsequent part may consist of both positive and negative optical power elements. This part of the optical instrument usually works with low aperture beams of rays. Consequently, it makes smaller residual aberrations. Usually here used lens telecentric relays or an optical component with negative power. The lens relay transfers an image of an intermediate image plane located in the head of the optical system on CCD. In the case of using optical elements with a negative optical power, their task is to lengthen the rear working distance, if it is necessary for the convenience of the whole optical system, as well as changes object linear magnification. Such type of optical system shown on Fig. 2.

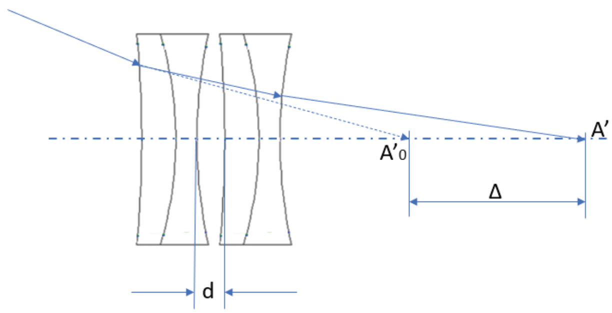

Fig. 2 Negative power two doublets lens group

Adjusting air gap **d** allows change linear magnification, as well as shift the image position along the optical axis. The double telecentric lens relay optical system shown on Fig.3. This relay consists two cemented doublets.

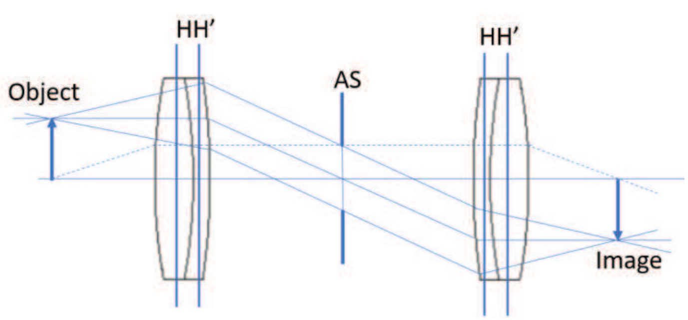

Fig.3 Double telecentric optical relay

The subsequent relay is double telecentric optical system. The relay object plane must match the head part image plane. The aperture stops AS (Fig. 3) defined image side NA. Most often relay lens components represents cemented doublets with positive power. In standard optical lens catalogs these elements are very common and therefore is easy to pick it up. The optical components shown in Figures 2 and 3 allow the most easily assembled optical system from standard elements.

4. Selection the optical elements from lens catalogs

When choosing any lens components from the catalog, there are two problems: the first is to find an optical element with a specific focus size and diameter, and the second is to choose an optical element with minimal residual aberrations. The solution for first problem concludes in the fact that during the optimization of the optical system, it is necessary to set such conditions for the focal lengths of the optical power elements so that they coincide with the focuses of the lenses and lens components, which are available in the catalog. If the optical system includes components with small residual aberrations, the total aberration of the entire system will be also small [2]. In the article [1] was developed a method for selecting standard optical elements with minimal residual aberrations. This method based on evaluation **K** lens parameter, which equal the multiplication of the glass refractive index and V-number (Abbe number). This expression was chosen because the refractive glass index and Abbe number are two most important glass constants. Theirs composition defined important lens ability of aberration correction. Proposed lens parameter comprised both glass constants. This parameter (K) defined by formula (3).

$$\mathrm{K} = \mathrm{n} \times \mathrm{v}; \quad (3)$$

Where **n** is glass refractive index and **v** is Abbe number. The cemented glass components (doublets) which consists of 2 lenses will describe by two different K parameters. One for crown glass lens with positive optical power and other for flint glass lens with negative optical power. The cemented doublet parameter (Kdb) defined next formula (4)

$$\mathrm{Kdb} = \frac{\mathrm{Kpl}}{\mathrm{Knl}}; \quad (4)$$

Where Kpl is **K** parameter for lens with positive power, Knl is **K** parameter for lens with negative power. The cemented triplet lens component is specific case. It will be considered as two cemented doublets, where two lenses made from the same glass. So total number of different glasses equal three, but we can operate with two different doublet lenses. The cemented triplet lens component **K** parameter will be defined by next expression (5).

$$\mathrm{Ktr} = \sqrt{Kdb_1^{\,2} + Kdb_2^{\,2}}; \quad (5)$$

Where Kdb_1 and Kdb_2 are K doublets parameters located inside cemented triplet lens. The K parameters for all type of lens components now defined. It should be noted here that the middle lens in the cemented triplet is treated as a common lens for the first and second doublets. Here it will be appropriate to give graphs of wave aberrations for two glued doublets from the catalog of the optical components. These doublets have the same focal lengths, but are made from different optical glasses. Those doublets shown on Fig.4.

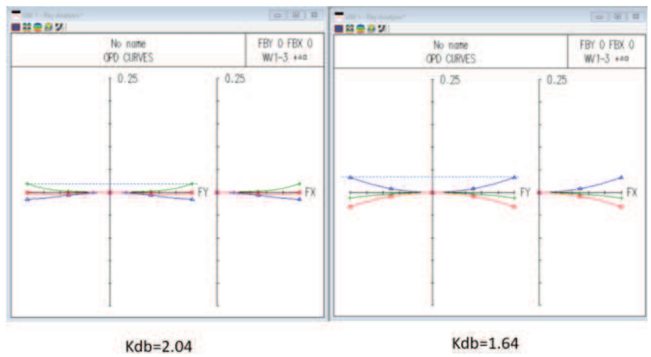

Fig.4 Cemented doublets wave aberrations graphs

The doublet with K parameter Kdb=2.04 made from glass pair N-Lak22/N-SF6 and has max. wave aberration equal 0.0055. The other doublet with Kdb=1.64 made from glass pair S-BAH11/N-SF10 and has max. wave aberration equal 0.011. The input NA for both doublets equal 0.04 and the focal length equal 35mm. Complete data for all types of optical components, including a summary table of results and graphs of aberrations, are given in article [1]. It is necessary to notice that the introduced parameter **K** uniquely determines the degree of correction of aberrations in the optical system.

5. Practical implementation method off-the-shelf optical elements

This method of replacing designed optical lens elements with off-the-shelf ones was applied in real optical systems that determine the quality of the measured surface in several different working distances. The optical schematics of such kind of optical systems were published in patent literature [3,4]. Initially, the optical systems of these devices were calculated without the use of lens elements from catalogs. Then the optical systems were reoptimized in such a way that they could use the standard lenses from catalogs. It should be noted that when choosing a lens from an optical catalog, preference was obtained lenses with a higher value of the K parameter. As practice has shown, such lenses have smaller residual aberration. The K parameter can be calculated for all types of optical components by using formulae (3)-(5). Practically, when optimizing an optical system for lens components, it is necessary to strive for focal lengths that are most common in the catalogs. For example, for the lenses and the lens components with the focus length equals: 5; 10; 12; 15; 20; 25 etc. mm the any catalog of optical components will provide the greatest choice of optical lens elements. Figure 4 represents an optical schematic of the apparatus for imaging an object in multichannel position [3]. This apparatus has two different working distances (WD) and respectively two image planes. As it was shown on Fig. 4 this device has two independent channels. Each channel should have equal linear magnification. The image sizes defined proper working distances for the object planes 1 and 2.

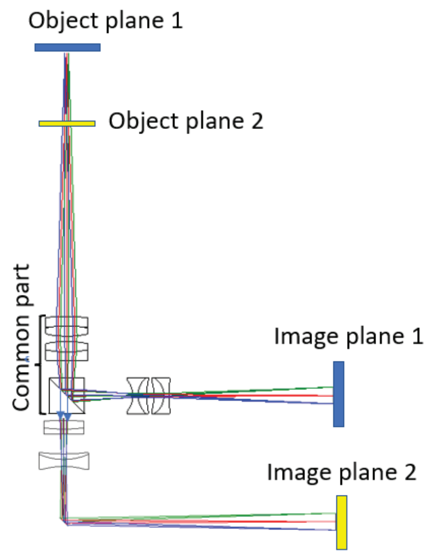

Fig. 4 Apparatus for imaging an object in multichannel position

By moving the object along the optical axis and checking its position according to the size of the image, its working position is determined. Design process an optical system from off-the-shelf lens components consists of two stages. The first stage includes the creation of an optical system from non-standard (custom) optical elements. At the second stage, there is a gradual replacement of custom optical elements with optical elements from catalogs. Let's consider the second stage in more detail. Before the second stage, an optical system that meets the requirements of the specification has already been created. It is necessary to replace the lens components while maintaining the image quality. To do this, in the catalogs it is necessary to find similar optical elements with the same focus values that have the components of the created system. If this is not possible, then it is necessary to re-optimize the optical system for the existing focal lengths of the lenses from the catalog. It should be noted here that an optical system consisting of two separate components is easily brought to the desired focus value. This can be easily accomplished by changing the air gap **d** between the lenses (formulas (1) and (2)).

When choosing optical components from catalogs to obtain an image with minimal residual aberrations, it is necessary to take into account the parameter **K** (formulas (3)-(5)) of the optical element and strive to find a component with its maximal value. This effect for any type of optical components was investigated in the article [1]. There is direct connection between magnitude of K lens parameter and residual aberrations of the optical component. **K** parameters data for all optical components are given in Table 1.

It should be noted that some components consist of the same pairs of glasses and therefore have the same K parameter values.

Optical components	Focal length, mm	Optics glass material	K-lens parameters	K-doublet parameter
45797-Edmunds optics	50	N-LAK22/NSF6	92.28/45.78	2.0157
62474-Edmunds optics	-60.5	N-BK7/N-SF5	97.3/53.94	1.804
48349-Edmunds optics	-18	N-BAF10/N-SF10	78.67/49.31	1.595
63723-Edmunds optics	100	N-BK7/N-SF5	97.3/53.94	1.804
45424-Edmunds optics	-35	N-BK7/N-SF5	97.3/53.94	1.804

Table 1 K parameters values for off-the-shelf optical components

The pair of optical doublets located in the Common part (Fig. 4) have equal focus distances and includes two identical lens doublets. These doublets have maximum value of K parameter and introduces a minimum of residual aberrations the other doublets work with smaller aperture angles and therefore they do not need to have a large **K** parameter value. For comparison **K** parameter value for glued glass pair CaF2/NSF6 equal 2.984, that is 48% larger than Maximum **K** number shown in Table 1. It is the reason why doublets including CaF2 are widely used in high numerical aperture optical systems, for examples in any type of microscope objective lenses with apochromatic aberration correction and NA>0.7. Figure 5 represents wave polychromatic aberration optical system shown on Figure 4. The aberration was calculated by using Monte Carlo method during tolerance analyses the optical system.

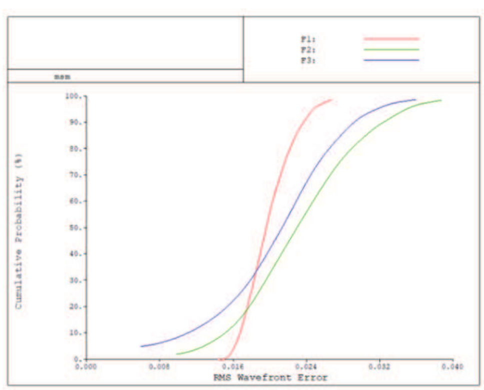

Fig. 5 Wavefront error of Apparatus for imaging an object in multichannel position

As shown in Figure 5, this optical system has diffraction limited level of wave aberration despite the fairly wide tolerances of optical elements. (All tolerances were taken from the drawings that are available in any catalog of off-the-shelf optical parts).

6. Conclusion

A method of replacing the custom optical lens elements with catalogue components has been developed. The essentials conditions have been developed for bringing whole optical system into a design form convenient for replacing custom optical components with off-the-shelf ones. Parameters allowing to evaluate aberration correction capabilities of off-the-shelf optical components were developed. An apparatus for the image of objects located at different distances is presented, in which all optical custom elements were subsided by lenses are made from off-the-shelf optical components. On the example of this apparatus, for all optical elements parameters that affect the image quality were analyze and the graphs of residual wave aberrations were shown. High image quality (diffraction limited for all working distances) confirm that proposed design method can be used for many cases. The price of optical systems in fully or partially made from standard optical elements will be much lower than the price of optical systems fully made from custom optical parts. It follows the tack of essay about one dignity of such optical systems, this is the speed of replacing any lens and the ability to have the necessary reserve.

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