Macro usage for analyzing of a telescopic system aberrations in ZEMAX

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Abstract. The experience of optical system aberration analysis using ZEMAX software demonstrates the necessity to acquire and combine data from different text windows such as windows of Longitudinal Aberration, Ray Fan, Field Curvature and Distortion, Lateral Colour etc. This routine operation takes much time and significantly slows down the design process. Moreover, an engineer should always remember about some features of data interpretation connected with different calculation algorithms in different optical schools. It instigated us to develop a macro that forms one-window aberration summary for afocal systems with proper data interpretation according to domestic optical scientific school.

1. Introduction

Optical system design is now closely connected with usage of computer-aided software such as ZEMAX, Code V, OSLO, OPAL, etc. Since 2007 ZEMAX is the basic program for scientific researches and student training at the RL2 department of Bauman State Technical University.

A macro in ZEMAX is an effective tool that extends standard program capabilities. Macros are complete subprograms designed to implement custom calculation algorithms. The language of macros uses operators, procedures and functions that interact with the data of an optical system model [1,11].

Macros are used when working with optical glass catalogs [3] and modelling inclined mirrors [4]. Some useful functions, such as setting the afocality of telescopic systems and calculating the chromatic differences of a wide bundle of rays, are implemented by the authors in the form of macros described in [5]. Moreover, ZEMAX is actively used by domestic authors to investigate aberrations of diffraction elements [6, 7], zoom optical systems [8]. So the use of macros may greatly simplify the work of researchers [9,10].

The current development of macros is connected with their application for image quality analysis.

Note that the content of aberration data listing depends on the type of an optical system but anyway it is necessary to get and analyze data formed by numerous software subprograms. In ZEMAX the data may be explicitly or implicitly contained in such textboxes as the Longitudinal Aberrations, Ray Fan, Field Curvature and Distortion, Lateral Color, as well as Prescription (an optical system specification) and Ray Trace (a text box with the results of ray tracing).

The simultaneous use of several text windows with the results of the image analysis requires a certain amount of time to find a desired value and considerably slows down the design process. An additional difficulty is connected with the windows' settings being limited by the program interface. For example sometimes it's impossible to set the required number of displayed values of the object or

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pupil coordinates. Moreover, data interpretation often requires to take into account the domestic practice of optical system design, for example the "sign rule", etc. [2].

The final step in designing is connected with the issue of working documentation. It may include standardized optical layout and aberration data listing for the optical system being developed. To automate this process we have created macros that form datasets for Aberration listing of the objective lens and the afocal system. All the data are displayed in a single window with a user-friendly structure that eliminates redundant information and takes into account the "sign rule". The dataset formed with the macro also contains the values that are not available in standard text analysis windows: chromatic differences, astigmatic differences, exit pupil positions for different chief ray angles.

The first feature of the aberration listing formed with the macro for afocal systems is that the values of transverse aberrations and field angles are displayed in the degree-arc minute-arc second format. The second feature takes into account that the Lateral color value is calculated as a difference of the chief ray angles for F' and C’ wavelengths.

2. Afocal system aberration listing macro
The aberration listing is a working document that contains data on the optical system itself, as well as the results of its aberration analysis.

2.1. General afocal system data
General data of the afocal system are the following: Г(γ) - visible (angular) magnification, D' - exit pupil diameter and 2ω - object space angular field of view.

The magnification and exit pupil diameter values are determined using the GetSystemData procedure, which generates a vector of values. Its resulting structure is similar to the General Lens Data section of the Prescription text box. The value of Г(γ) is kept in the vector’s field 17, and the exit pupil diameter D’ corresponds to field 13.

The angular field of view value is retrieved from the Field Data dialog box using the MaxF() function. The values are then displayed in the text window using the Print procedure.

A fragment of the macro program to extract and display general afocal system data is as follows:

```
GetSystemData 2
Format 4.1
Print "Г = ",VEC2(17)
Print "D' = ",VEC2(13)
Print "2в = ", MAXF() * 2
```

A fragment of the resulting text box with the general data is shown in Figure 1.

2.2. Optical system surface data summary
The optical system surface data include curvature radii of surfaces, axial distances, glass names, refraction index, surface apertures and sag data.

The curvature radii r, axial distances d, and glass names values are extracted from the Lens Data Editor using the functions Radi(i), Thic(i), $Glass(i), respectively, where i is the surface number.

The determination of the refraction index in ZPL (ZEMAX Programming Language) may be implemented in three different ways:

- By means of direct substitution of the wavelength in the dispersion formulas of Schott, Sellmeier, Herzberger.
- Using the Indx(i) function that returns the value of the refraction index after the i-th surface for the primary wavelength.
- Using the Grin(i, λ, x, y, z) function that returns the refractive index value after the i-th surface for the wavelength λ at the point with x, y, z coordinates.

The macro being discussed uses the Grin function.
To determine the clear apertures and sag values, the standard EdgeSag macro was adapted. A fragment of the resulting text box with the surface data summary is shown in Figure 1.

2.3. Axial ray aberrations

The axial beam summary table contains the information about longitudinal and transverse aberrations for the paraxial ray and for the rays going at the pupil zone and the pupil edge. Determining the aberrations is made in the exit pupil plane. To get the necessary data the ray tracing procedure <RayTrace Hx, Hy, Px, Py, wavelength> is used. Hx, Hy are the relative coordinates of the object, Px, Py are the relative heights of the entrance pupil in sagittal and tangential planes, respectively. Wavelength is the wavelength number in the WaveLength dialog box.

Having been performed the procedure provides the coordinates of the points where the ray meets the surfaces and the values of direction cosines of the ray at these points. To compile the Aberration listing tables we used the values of RayL (NSur ()), RayM (NSur ()), RayN (NSur ()). They are the direction cosines of the ray with x, y, z axes, respectively, at the ray and exit pupil intersection point. The value RayY (NSur ()) is the y coordinate of this point.

Note that tracing a ray at zero height one should set not a zero Py value but a small finite value, for example, 0.00001.

To calculate the longitudinal spherical aberration we used the expression:

$$\Delta s' = -\frac{1000 \cdot \text{RayM}(\text{NSur}())}{\text{RayY}(\text{NSur}()) - \text{RayN}(\text{NSur}())}$$

where the minus sign is used to bring the aberration value in correspondence with the "sign rule" adopted in Russia.

The view of the axial ray aberration table is shown in Figure 2.

Since the image for the afocal system is at infinity, the axial ray slope at the exit pupil is the same as the transverse spherical aberration. The values of transverse aberrations are also brought in correspondence with the "sign rule" and displayed in the format of degrees-arc minutes-arc seconds [5]. In addition, the calculation of chromatic differences is made.
2.4. Tangential off-axis ray aberrations
Aberrations for a wide off-axis tangential ray bundle are calculated in the exit pupil plane. The aberration is the deviation of the current ray from the chief ray at the primary wavelength. In this case, the chief ray is considered to be the ray going through the center of the vignetted pupil, which means the chief ray may not necessarily pass through the center of the stop.

The view of the tangential off-axis ray aberration table is shown in Figure 3.

2.5. Sagittal off-axis ray aberrations
Aberrations for a wide off-axis sagittal ray bundle are calculated in the exit pupil plane. The projections of deviations of the current ray from the chief ray at the primary wavelength on xz and yz planes are calculated as follows:

\[
\Delta \psi' = - \arcsin \left( \frac{\text{RayL}(\text{NSur}(\_))}{\text{RayN}(\text{NSur}(\_))} \right)
\]

\[
\Delta \sigma' = \sigma'_0 - \arcsin \left( \frac{\text{RayM}(\text{NSur}(\_))}{\text{RayM}(\text{NSur}(\_))} \right)
\]

where \( \sigma'_0 \) is the chief ray angle in the exit pupil plane.

The view of the sagittal off-axis ray aberration table is shown in Figure 4.
2.6. Chief ray aberrations
The table of the chief ray aberrations contains the data about the exit pupil position, tangential and sagittal curvature values, as well as astigmatism, distortion and lateral colour.

The exit pupil position is determined for the chief ray going through the centre of a symmetrically vignetted pupil according to the formula:

\[ s'_{p'} = \text{Thic}(\text{NSur}(\quad) - 1)) - \frac{\text{RayY}(\text{NSur}(\quad)) - \text{RayN}(\text{NSur}(\quad))}{\text{RayM}(\text{NSur}(\quad))} \]  

When determining the distortion Paraxial On mode was activated to trace a paraxial ray.

The Lateral color is calculated as a difference between the chief ray angles in the exit pupil plane for the wavelengths F' and C'.

The tangential and sagittal curvatures are determined based on the processing of the text file generated by the GetTextFile procedure for FCD analysis. The view of the chief ray aberration table is shown in Figure 5.

Thus the macro has been developed to automate data acquiring for standardized Aberration listing of an optical system. Having been formed one-window data set contains the information about general system data, surface data summary and tables of aberrations for afocal systems. All the data have been brought in correspondence with the requirements of GOST, "sign rule" and units of displayed values.

![Figure 5. A fragment of the text box with the chief ray aberration table.](image)

3. References
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