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MACHINE DESIGN

COMPLEXITY OF DESIGNING OPTICAL SYSTEMS

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***Abstract**: Process of designing optical system that fulfils all necessary requirements is very complex and consists from several steps. First step is optical design and optimization of an optical system following by mechanical design and definition of quality of the optical system and its elements. The program OSLO, which is presented in this monograph, offers very good connectivity between the optical design program and the mechanical design (CAD) program.*

The review of the optical and the mechanical design of the double Gauss lens using programs OSLO and Mechanical desktop is given in this monograph.

Keywords: *design, optical system, lens, optimization*

1. INTRODUCTION

Optical designers, mechanical engineers and production engineers are confronted with great problems in order to produce an optical device which satisfies all necessary parameters that defines quality of an optical system. Basic parameters which an optical designer ought to consider are geometrical parameters like a curvature of a reflecting or a refracting surface, an axial thickness, a clear aperture, properties of optical materials like the index of refraction, the Abbe number, the homogeneity of materials, and the rate of reflection or transmission thorough the optical elements.

Complexity of optical devices can be shown on an example of an optical system with only two lenses. Two lenses have four spherical surfaces defined with corresponding radius of curvature, three axial separations, two clear apertures and two optical materials defined with the index of refraction and the Abbe number. This means that the optical system with only two lenses have 13 construction parameters that can be varied during design and optimization. Also each of these parameters has its tolerances. Those are only optical components and it is clear that each optical device consists at least from optical and mechanical components. The mechanical components have their complexity, parameters for design and their tolerances. It is necessary to know that the quality of optical surface is defined not only with the production tolerances but also with the errors in optical material and the errors in the production of optical elements. The errors in optical materials are bubbles, striae and internal residual stress.

The errors in the production of optical elements are various and most often are errors in smoothness and spheres, errors in focus, surface errors and tension errors caused by the machining process. There are also allowed errors in transparency and reflection etc. If requirements for quality of portable mechanic parts are added to these elements of quality, we come to very complex requirements that can be fulfilled if the device is designed by the designer of optical devices with great experience and knowledge of optical devices and their function.

In addition to the 3D CAD programs for design of mechanical parts for the optical devices, today there exist quite a number of lens design programs. One of them is the program OSLO (from Lambda Research Corporation, USA) which makes possible designing various optical systems from simple ones to very complex ones. The program OSLO allows the complete analysis and optimization of optical systems and definition and analysis of tolerances for optical systems. The program OSLO also enables exchange of data between the optical design program and the 3D CAD program and has support for production of optical devices.

2. OPTICAL SYSTEM

The optical system is group of optical elements designed to collect and to direct light (optical radiation) to perform some definite optical function. The optical device can be very complex system consisted from various optical and optoelectronic components like lenses, prisms, mirrors, filters, beam splitters, image intensifiers, and detectors [1]. The task of designing such complex optical device can be very complicated if one wants to fulfil all requirements for design characteristics and image quality.

The optical system design can be separated at following phases:

- the problem definition;
- the ideal optical system design and selection of the appropriate starting optical system;
- the complete geometrical and physical optical analysis;
- the optimization of an optical system;
- the final analysis of optimized optical system;
- the definition of optical tolerances and the tolerance analysis (the analysis of influence of optical tolerances on image quality);
- the preparation for production of optical elements.

End users define the requirements and the restrictions for the desired optical system and an optical system designer ought to translate those restrictions to detailed optical specifications like the field of view, the effective focal length, and to define requirements for the image quality. In the phase of ideal optical system design, an optical designer needs to decide, among the other things, about following:

- image forming elements in an optical system will be only lenses (the refractive optical system), only mirrors (the reflective optical system) or an optical system will have both lenses and mirrors;
- number of optical elements (lenses, mirrors, prisms, plan parallel plates) which will build an optical system.

During ideal optical system design an optical designer calculates necessary paraxial quantities like the effective focal length, the back focal length, the object and the image distance, the numerical aperture, various types of magnifications, the position and dimension of the entrance and the exit pupil, the total optical system length.

When necessary paraxial quantities are calculated an optical designer can define or more often choose starting optical system from the existing optical system database. There are several commercial optical system databases. It is important to notice that the ideal optical system design is usually done by hand calculation, and the definition of the starting optical system is first phase where optical design program is necessary. If one wants to define an optical system in any optical design program following parameters are necessary:

- the radius of curvature for each refracting or reflecting surface of an optical system;
- the axial separation between two surfaces of an optical system;
- type of optical material (usually the optical glass) from which optical elements are made;
- the clear aperture for each surface of an optical system.

When the starting optical system is entered in the optical design program, meaning when geometry of an optical system is defined and when the ray scheme is defined, optical designer can perform various analyses. The ray scheme is set of rays which are traced through an optical system in order to calculate aberrations. In standard optical design programs there are large number of various analyses that can be done. Purpose of all this analysis is to define performance of optical systems. There are two ways to define performance of an optical system, or more exactly, the image quality of an optical system: traditional and modern. The traditional way of describing the image quality is based on:

- the calculation of five principal monochromatic aberrations: the spherical aberration, the coma, the astigmatism, the field curvature and the distortion;
- the calculation of the transverse ray aberrations;
- the calculation of the chromatic aberrations;
- the calculation of the optical path difference;
- the calculation of the wave aberrations.

The modern way of describing the image quality is based on:

- the spot diagram;
- the geometrical and the diffraction MTF (modulation transfer function);
- the through-focus spot diagram and the through-focus MTF for finding the best image position;
- the point spread function and the line spread function;
- the geometrical and the diffraction encircled energy.

When all needed analysis are done, an optical designer will have clear picture whether starting optical systems fulfils all necessary requirements. In most cases starting optical system will not fulfill all requirements and optimization of the optical system needed.

The goal of optimization is to take a starting optical system and change it to improve its performance (the starting optical system should have a necessary number of optical surfaces of suitable types, since the optimization can change only the values of the parameters not the number or type of surfaces). Traditionally optical design programs used some kind of the dumped least squares optimization. The modern optical design programs also use global optimization procedures like the genetic algorithms and the evolution strategies [2].

When optimization of an optical system is finished, an optical designer needs to make analysis of a new optimized optical system to confirm that all requirements are fulfilled. After analysis an optical designer ought to define optical tolerances for each optical element and to analyse the influence of optical tolerances on the image quality of an optical system [3].

3. OPTICAL DESIGN PROGRAM

Optical design programs can be classified in two groups according to the way they are created [4]. First group of programs consist of optical design programs that are developed for solving engineering problems and as an aide in research. Common characteristic of all programs in that group is that they are developed for internal use and that they were not commercial programs. Later after long period of development (usually more than 20 years) they become commercial programs. Most important optical design programs in the first group are: the CODE V from Optical Research Associates, the ASAP from Brault Research Organization Inc., the OSLO from Lambda Research Corporation. All this programs are mainly developed for UNIX graphical workstations and when PC computers and MS Windows are become powerful enough they are ported from UNIX to Windows.

Second group of programs consist of programs that are developed from the start as a commercial optical design programs. They are developed only for PC computers and MS Windows, and their development period was at most 10 years. Now after rather long period of development some optical design programs from the second group can be as powerful as programs from the first group. Most important optical design programs in the second group are: the ZEMAX from Zemax Development Corporation, the OPTALIX from Optenso, and the OPTIKWERKS from Optikwerks Inc.

The standard optical design programs like the OSLO or the ZEMAX usually offers to an optical designer following possibilities [5]:

- the design of various optical elements;
- the design of complete optical system, which may consist from larger number of lenses, mirror and/or prisms;

- the design of system which consists from the light source, the optical or the optoelectronic system and the detector;
- the complete analysis of an optical system including the aberrational analysis, the spot diagram, the MTF calculation and the encircled energy;
- various non standard ray trace methods like the polarization ray trace and the non-sequential ray trace;
- various optimization methods for finding optimum optical system.

Some optical design programs have special macro programming language which allows possibility for optical designer to program special non standard procedures for further analysis of optical systems. Modern optical and optoelectronic systems are very complex devices and it may emerge necessity for development special procedures during design, analysis or optimization of such systems.
One of most important features that the optical design program can have is the optimization of optical systems. The standard method for the optimization is some kind of the dumped least squares (DLS) method. Optical design programs differ among themselves by the way they implement the DLS method and how they control optimization process, Some optical design programs in addition to the standard DLS method have some modern optimization methods like the genetic algorithms or the simulated annealing. In the mathematical theory of the optimization it can be shown that any kind of the DLS method can only find the local optimum and that modern optimization methods can find several local optimums and even the global optimum.

4. OPTICAL AND MECHANICAL DESIGN OF DOUBLE GAUSS LENS

In this monograph optical design program OSLO (**O**ptical **S**oftware for **L**ayout and **O**ptimization) made by Lambda Research Corporation, USA is presented [6]. The program OSLO among many standard features, that other optical design programs also have, have possibility of exporting designed optical systems in CAD programs by using DXF file format for exchange data. The process of designing optical system and exporting finished design to the CAD program is shown at example of the double Gauss lens. The double Gauss lens is an objective used in photographic cameras and video cameras. It is example of moderate complex optical system.

At figure 1 the optical layout and partially displayed input data of the double Gauss lens are shown.

There are several different types of the double Gauss lens that can be found in available literature [7, 8]. In this monograph the Biotar type of the double Gauss lens is used as the starting point for design of an optical system. Design requirements for the optical system are the effective focal length 50 mm, the relative aperture f/2, the total field angle 2ω = 40°. This is standard requirements for the objective for 35 mm film photographic camera. From the figure 1 one can see that the double Gauss lens have 6 lenses (2 singles and 2 doublets) and 12 spherical refracting surfaces.

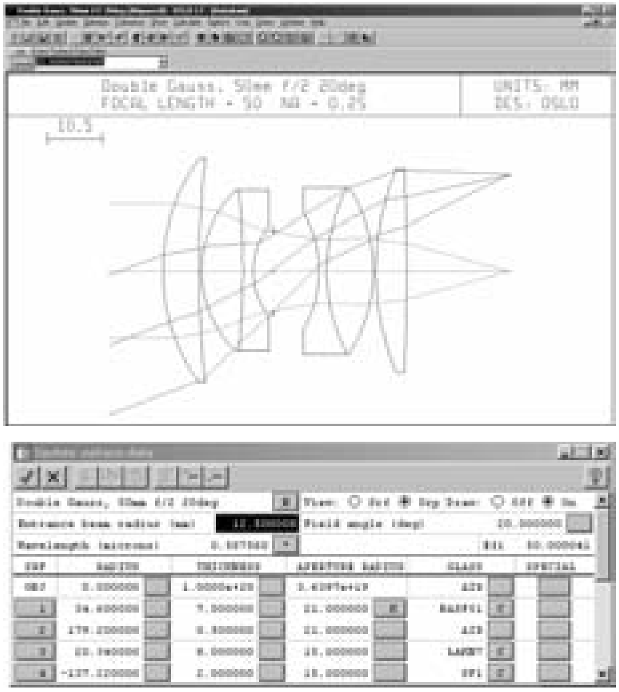


Figure 1. The optical layout of the double Gauss lens and partially displayed input data

At figure 2 the standard aberrational analyses showing the monochromatic and the chromatic aberrations are displayed.

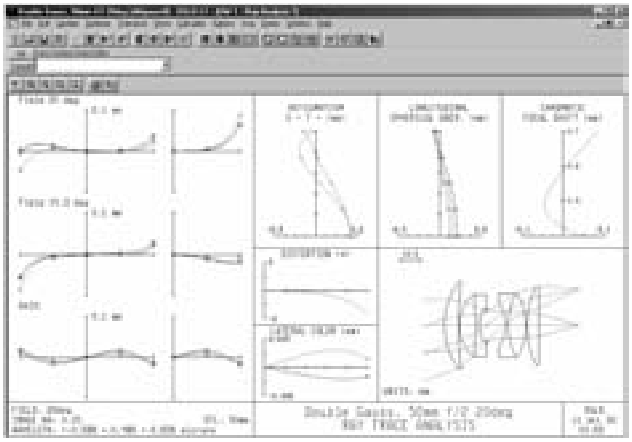


Figure 2. The aberrtional analysis of the starting double Gauss lens

Optical designer ought to carefully study results obtained by the aberrational analysis and decide whether starting optical system fulfils all design requirements or not. If design requirements are not fulfilled then the starting optical system ought to be changed, usually through the optimization, in order to reach designed requirements.

The optimization is automatic process but an optical designer ought to provide the starting conditions for optimization. This means that optical designer ought to provide the variable construction parameters and to define the merit function with the boundary conditions. In modern optical design programs there are very well defined merit functions that are suitable for most optimization purposes, so optical designer ought to concentrate only on clever definition of variable construction parameters.

At figure 3 designed double Gauss lens is presented as the 3D model in the program OSLO.

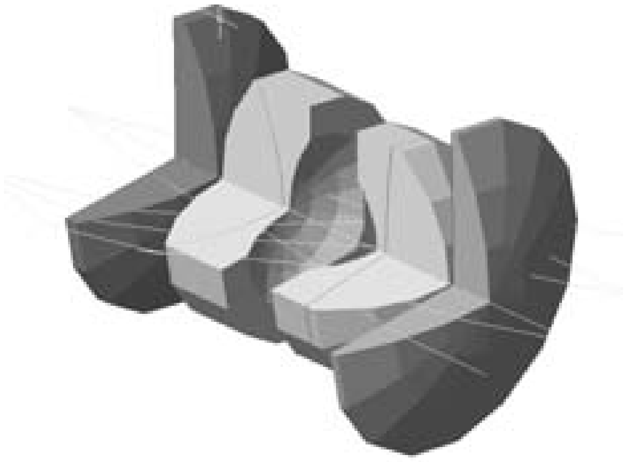


Figure 3. The 3D model of the double Gauss lens in the program OSLO

With use of "Export to CAD" model in "Mechanical desktop" program identical 3D model of Gauss lens is gained and that provides the possibility for its further modeling and design of mechanical elements.

After definition of work plane in "Mechanical desktop", we start 2D Sketching tools needed to draw sketches. For example, lines, arches, circles, rectangles and curves can be chosen and drown. Sketch can be easily drawn but it needs to be converted to profile to make extruded, curved, rotating or risen details to which can be applied quotes and limits.

After definition and limitation of profile rotating details are made, like objective covers (figures 4 and 5). Other mechanical elements of the objective are designed.

Figure 4. Design of objective covers

Compositions can be presented as fragmented pictures - scenes in Desktop Browser. Scenes split up elements due to fragmentation factor. Final composition of mechanical and optical elements of the objective is presented in figure 6

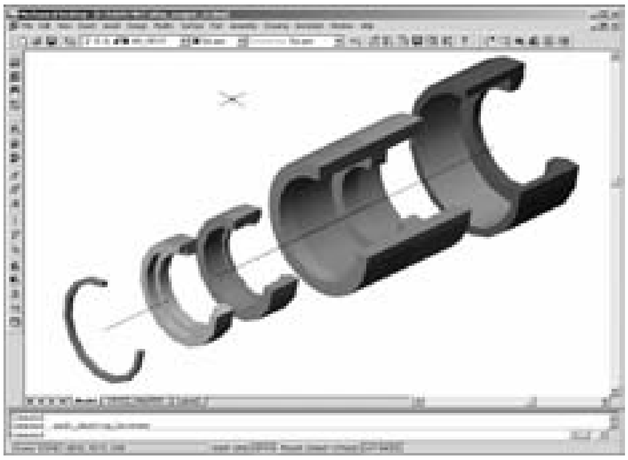


Figure 5. Composition of objective covers - 3D

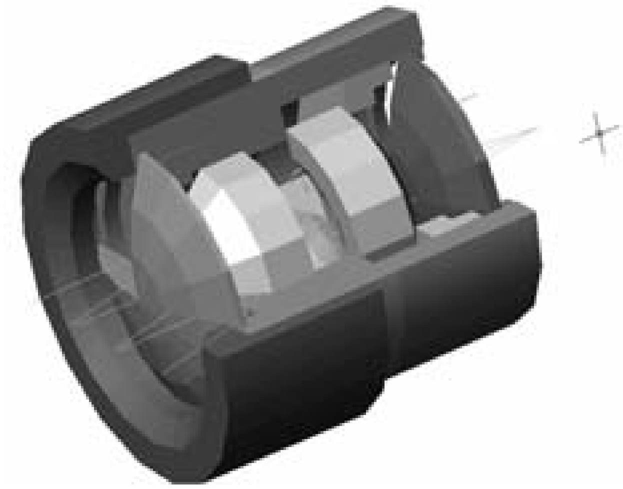


Figure 6. Mechanical parts of the objective and its composition with optical elements

5. OPTICAL SYSTEM ANALYSIS

There are two ways of doing optical system analysis: the traditional with the aberrational analysis and the modern with the spot diagrams, the MTF and the encircled energy.

The aberrations can be defined as any systematic deviation from an ideal path of the image forming rays passing through an optical system, which causes the image to be imperfect. In other words the aberrations are differences from the real and the ideal image. The ideal image is formed under assumption that all rays, emerging from the one point on the object, after traversing the optical system, pass through one point on the image. The real image is calculated by the ray trace through the optical system. For the paraxial rays (rays that are close to the optical axis) the aberrations are small and can be neglected. But for all other rays that are passing on the finite distance from the optical axis and with the finite field angle the aberrations becomes considerable because they distort image.

The basic reason for the aberrations is in the fact that the lenses are formed from the spherical surfaces, which do not refract rays at the same way as it is assumed in the paraxial approximation. These aberrations are called the geometrical aberrations. Another reason for the aberrations is connected with the light dispersion. Since the index of refraction for the optical glass is the function of the light wavelength then the effective focal length and the other optical system characteristics are also a function of the wavelength. Therefore the rays emitted from the same object point and having different wavelengths after passing through the optical system do not converge in the same image point although each of them alone can be ideal. This kind of aberrations is called the chromatic aberrations.

For the purpose of optical design aberrations are broadly divided into two large groups: the monochromatic and the chromatic aberrations. The monochromatic aberrations or the geometrical aberrations are aberrations occurring when the optical system is illuminated by monochromatic light. The chromatic aberrations occur due to variations in optical system properties with wavelength of the incident polychromatic radiation. In practice, aberrations occur in combinations rather than alone. The system of classifying aberrations makes the analysis much simpler and gives a good description of optical system image quality.

Normally aberrations are measured by the amount by which rays miss the paraxial image point. The aberrations are measured by the linear displacement of the points at which real rays intersect the image surface, which is defined as image plane for the perfect optical system.

It should be kept in mind that aberrations are unavoidable in actual optical systems and one of the aims of optical design is to correct optical system being designed for aberrations. Some aberrations, however, inevitably remain and the purpose of the image quality evaluations is to determine how large the residual aberrations are. In general a modern optical design takes aberrations into account by solving following problems:

- determine the residual aberrations for an optical system with specified constructional parameters;
- evaluate the variable constructional parameters for an optical system which will keep the residual aberrations within the specified tolerable values. These tolerable values can be derived from the purpose of the optical system.

The general definition of the spherical aberration can be the change of the focal length with the change of aperture. Main cause for the spherical aberration is that the angle between the incident ray (which is parallel with the optical axis) and the normal to the spherical surface is not the same at different heights. This angle is growing and therefore the rays on the larger distances from the optical axis during the refraction through the optical surface are turned with greater angle of refraction toward the optical axis and because of that cross the optical axis before the rays on the lower heights (figure 7).

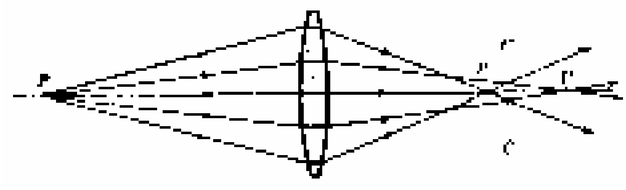


Figure 7. Spherical aberration

The coma appears for the wide ray bundles entering an optical system at a certain angle to the optical axis. The coma is the aberration which essentially spoils the symmetry of the ray bundle, which after passing through the optical system is no longer symmetric in relation to the principal ray. The corrupted symmetry for the ray exiting the optical system is explained by unequal refracting conditions for rays entering the optical system in different zones of the entrance pupil. As the result of this asymmetry the spot, which is produced by the dispersion of the rays starting from the extra-axial object point and passing through the optical system, loses its circular form characteristic for the spherical aberration and obtains the form of the comet with tail (figure 8).

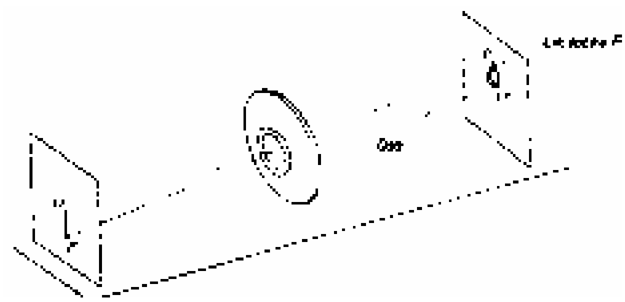


Figure 8. Coma

The astigmatism is a phenomenon where the rays from one pencil of rays, viewed in two mutual normal planes (the meridian and the sagital) after refraction through the optical system, do not intersect in the one point nor they intersect in the paraxial image plane but they form an image – the meridian and the sagital focal line which are located at a certain distance from the paraxial image plane and under the 90° angle from which one focal line is horizontal and the other is vertical. The meridian plane can be defined as a plane set through the object point and containing the optical axis. The sagital plane is a plane set through the object point and normal to the meridian plane (figure 9).

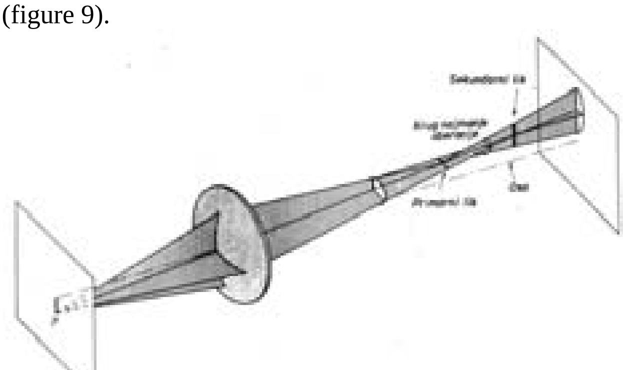
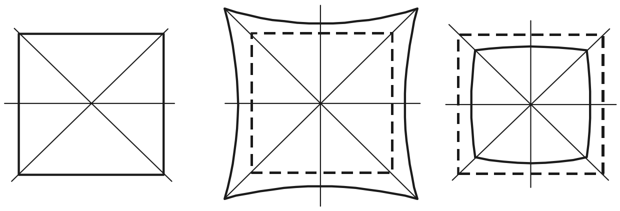


Figure 9. Astigmatism

The field curvature is closely connected with the astigmatism and they are always discussed together. The physical essence of the aberration field curvature is that the flat image after projection through the optical system will not be any more flat but will be curved i.e. if the object is positioned in the plane after the projection through the optical system image will not be in the plane but in the space and it will form paraboloid.

The distortion in regard to all other aberrations has special features. It does not cause the vagueness of the object image. If in the optical system all other aberrations are corrected and only pure distortion is left, then the images of all the object points will be also clear points. The distortion causes the deformation of the object image in the geometrical sense. In other words the distortion is an aberration appearing as the curvature of straight lines in the object, i.e. as a breakdown of the geometric similarity between an object and an image.

The distortion arises from the incomplete realization of the well known geometrical optics law that the transverse magnification for the pair of conjugated and normal to the optical axis planes is constant. Nonfeasance of this law leads to the deformation of the image (figure 10).



(a) *(b)* *(c)*

Figure 10. Distortion
(a) – undistorted image, (b) – positive or pincushion distortion, (c) – negative or barrel distortion

Spot diagram represents method for geometrical analysis of point object image quality. Large numbers of rays are traced through the optical system and their intersection with the image plane or the detector plane is considered. The spot diagram is calculated by dividing entrance pupil at large number of equal areas and ray is traced through the center of each area. The intersection of each ray, which is traced through the whole optical system, with the detector plane is drawn. Obtained image consists from large number of spots. Each ray represents small equal part of light energy at the detector, so the density of rays at detector can represent energy at detector. There are two possible ways of the spot diagram calculation: the geometrical spot diagram and the RMS spot diagram.

The geometrical spot diagram is defined by the distance from the reference point to the point of intersection of the farthest ray that is traced through the optical system, with the detector plane. Intersection of the principal ray with the detector plane is usually chosen for reference point. The geometrical spot diagram can be represented by the radius of circle with the center in the reference point and which encircle all rays that are passed through the optical system.

The RMS spot diagram is defined by the root mean square (RMS) of the distances of all rays that are traced through the optical system, from the reference point. The RMS spot diagram gives a rough idea of the spread of rays, since it depends upon every ray.

The optical transfer function (OTF) can be defined by capability of optical system to transform the distribution of light intensity from the object plane to the image plane. Assuming the distribution of light energy in the object plane is known then corresponding distribution of light energy in the image plane can be calculated if the OTF is known. The OTF can be defined as:

$$OTF = MTF \cdot e^{(i \cdot PTF)}$$

where is:
MTF – the modulation transfer function;
PTF – the phase transfer function.

From physical standpoint larger importance has the MTF then the PTF. The MTF represents a measurement of the ability of an optical system to transfer various levels of details from the object plane to the image plane. The MTF is usually shown as a diagram of the degree of contrast (modulation) in the image plane against spatial frequency. The PTF represents displacement of the image according to the optical axis for off axis rays.

The MTF contains the information about influence of aberrations and diffraction on transfer of light energy through an optical system. In order to exactly calculate MTF one ought to know whether an optical system is the diffraction limited or the aberration limited. For the diffraction limited optical systems (the diffraction is greater then aberrations) the diffraction MTF is needed to be calculated. For the aberration limited optical systems (the aberrations are larger then the diffraction and the diffraction can be neglected) the geometrical approximation of the MTF is needed to be calculated.

The encircled energy is energy percentage plotted as a function of image diameter. In some cases, when optical system uses a CCD as a sensor, it is more useful to know how much of the total energy is contained within a circle or square of a given size. Usually it is considered that 80% of energy from a point object should be concentrated on a circle with radius smaller then CCD pixel radius. Similar to the MTF calculation, the encircled energy can be calculated as the geometrical encircled energy and as the diffraction encircled energy. For the aberration limited optical systems the geometrical encircled energy is calculated based on spot diagram. For the diffraction limited optical systems the diffraction encircled energy is calculated based on point spread function.

6. OPTICAL SYSTEM OPTIMIZATION

The optimization concept is fairly simple but its implementation can be quite complex. One can define it as the determination of the set of system configuration variables which minimizes the deviation of actual performance from targeted goals without violating boundary limitations. This simply stated problem becomes a complex problem when the number of variables and targets are large, errors are nonlinear functions of the variables, and the errors are not orthogonal to each other with respect to the variables. In the typical optical system optimization case, all of these conditions are true to a certain degree [12].

When working with various types of optimization methods one usually define a single number, called a merit function, to characterize actual system performance compliance with the targeted system performance. In other words the merit function value is the measure of the effectiveness of the optimization method as it is the goal of the optimization to reduce the merit function value.

The selection of an appropriate merit function for the optimization is fundamental to the successful outcome of the process. From the mathematical point of view the most appropriate merit function is a function in the quadratic form. The merit function can be defined as a sum of squares of the aberrations:

$$\psi = \sum_{i=1}^{m} (\omega_i \cdot f_i)^2$$

where is:
ψ - the merit function value;
m - the number of parameters of optimization;
ω_i – the waiting factor for each calculated aberration;
f_i - each aberration that is calculated by ray trace through the optical system.

The waiting factor for each calculated aberration is necessary because, the merit function can consists of different types of aberrations (transverse ray, angular, waveform) that may differ very much. In order to be able to compare aberrations and to reduce their values the program has to bring them to similar values.

There are two kinds of optimization procedures: classical and modern. The classical optimization (typical representative is dumped least squares – DLS method) can only find local minimum. Because the optimization of the merit function will find a local minimum, it is up to the optical designer to bring the starting optical system to a suitable quality before optimization so that the local minimum is close to a global minimum. In other words, it is not possible to choose five plane-parallel plates of arbitrarily chosen glass and expect the program to find an optimum solution.

Modern optimization methods, which are also called global optimization methods, try to find global minimum but although there have been recent advances in the development of global optimization techniques the user must be careful with them. The global optimization can be a useful tool in the lens-designer's toolbox, but it will not satisfy the designer's wish to find the best optical system automatically. In general, the global optimization can produce numerous starting points from which the designer can locally optimize [13 - 15].

The DLS optimization belongs to a broader group of linear optimization models, which do not take any explicit account of the fact that there may be many local minima of the merit function in the space of all variables. The number of local minima depends on the merit function and number of variables. The damped least squares generally drives the merit function to the local minima nearest the starting optical system. The optical designer has several tools besides the optical design program, which allows him to find a satisfactory optical system. These tools are:

- the selection of a promising starting optical system. If one optical system does not give required quality, the optical designer might try another entirely different optical system;
- the choice of optimization variables. A poor choice of variables may even prevent a linear convergence;
- the weights used in construction of the merit function. Good selection of weights is essential in balancing the aberrations;
- the choice of the damping factor (adaptive or multiplicative damping) and the choice of modification of the complete merit function;

These tools are highly dependent on the skill and experience of the designer. Even an experienced designer may have difficulty in searching out a satisfactory solution for a “state of art” design requirement.

One class of very promising optimization methods are evolutionary optimization methods. Evolutionary optimization is based on analogy in the nature. All life in our planet evolved according to the Darwinian theory of the evolution. So we try to apply a simplified Darwinian theory of the evolution in the technical systems optimization. There are two main kinds of evolutionary optimization: genetic algorithms and evolutionary strategies. Genetic algorithms emphasize selection process and crossover [16], while evolutionary strategies emphasize normally distributed mutations [17].

Genetic algorithms use a direct analogy with natural behavior. They work with a population of individuals, each representing a possible solution to a given problem. Each individual is assigned a merit function value according to how good a solution to the problem is. The highly fit individuals are given chance to reproduce by cross breeding with other highly fit parents. The least fit members of the population are less likely to get selected for reproduction and so die out.

A whole new population of possible solutions is thus produced by selecting the best individuals from the current generation and mating them to produce a new set of individuals. This new generation contains a higher proportion of the characteristics possessed by the good members of the previous generation. In this way over many generations, good characteristics are spread through out the population, being mixed and exchanged with other good characteristics as they go. By favoring the mating of the more fit individuals, the most promising areas of the optimization space are explored. This leads the population to converge to an optimal solution to the problem.

7. QUALITY OF OPTICAL ELEMENTS

Design of optical device does not end here. The next step is definition of mechanical and optical elements quality. Firstly, the tolerance in production of mechanical elements with limits of increased accuracy is defined, according to JUS ISO 2768 - f (class of tolerance - fine). During the design of optical elements, requirements for picture quality are not requested to be fulfilled in advance. These requirements are set for the optical elements and the installation of optical elements.

Quality of optical elements is defined based on allowed errors for optical elements that can be ranked in two groups.

These are errors in material and errors of machining. Errors in material are bubbles, fibers and tensions. Errors of machining are different, and the most common are errors in smoothness and sphere, errors in lens focus, surface errors, errors in angles at prisms, and tension errors caused by machining. Also, allowed errors in dimensions, transparency and reflection are defined. Required quality is set by DIN 3140 standard, although some other standards (GOST 3521) are used for details labeling.

Errors in material and machining according to DIN 3140 are labeled like in table 1.

Table 1. Marks and symbols for optical elements drawing

Symbol	Explanation	Standard DIN 3140
1	Bubbles	2
2	Grooves	3
3	Error in contiguity	5
4	Error in focus	6
5	Surface errors	7
6	Stress	4
50	Spots with coating damage	10
with no symbol	Unprocessed	
∪	Bright, transparent	
·	Grinded. rough	
· ·	Grinded, average	
	Grinded, fine	
· · ·	Grinded, the finest	
	Polished, rough	8
	Polished, average	
	Polished, fine	
	Polished, the finest	
	Surface data according to DIN ISO 1302	
	Reflection layer on front surface	
	Reflection layer on back surface	
	Division layer	9
	Layer with reduced reflection	
	Special layer	
	Lacquered layer	

Bubbles are described as pores in material filled with gas or ingredients. There are transparent and absorbing bubbles. Comparing to transparent bubbles that are caused by restraining of gas during process, absorbing bubbles causes much greater error in picture quality and they have twice lower tolerance. Bubbles can be of regular shape, mainly circular in cross section, rarely irregular, Classification of bubbles is significant for determination of raw material quality. It is determined by diameter and number of bubbles in total volume. Therefore, beside dimensions, bubbles size and number as

$$1/A \times S$$

where

A - number and

S - diameter of the bubble are labeled on the construction profile of raw material.

Grooves are commonly unwanted, usually aggregations in form of ropes or stripes. They are caused by unequal refraction index in parts of optical material volume. Therefore, effect of grooves on surface of optical element is mainly determined by their shape, size and difference in reflection index (n_{glass} - n_{groove}). According to shape, there can be thread grooves, thread grooves with inference in a shape of a dot and stripe grooves.

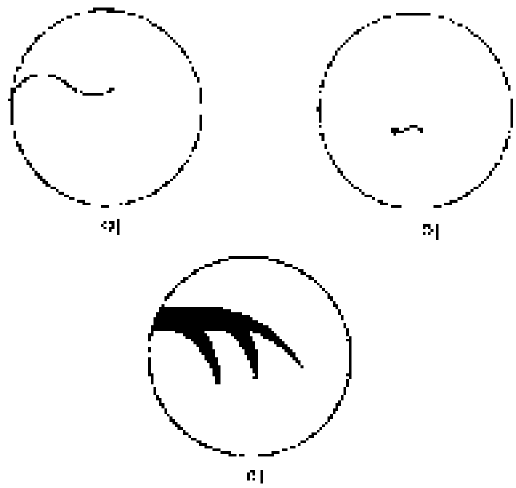


Figure 8. Basic shapes of grooves

Considering the fact that sphere surfaces of lens are processed in turns, first one and then the other radius, there is small probability that the edge of the lens will be adjusted to both centers of the sphere. Error in focus can be expressed in two ways: as deviation of geometric axis from optical (a), or as deviation of tangent angle from parallel beam that falls on the sphere (b).

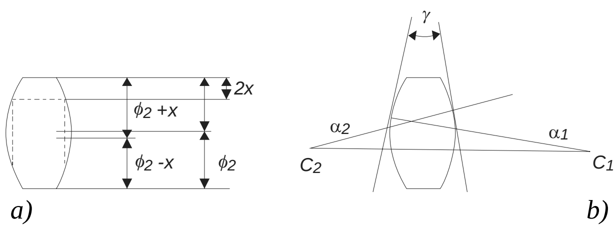


Figure 9. Errors in focus

Number mark for tolerance of focus contains number 4 and the value of surface incline angle κ, where for κ value the maximum value in minutes 4 / κ is taken.

Deviation of processed optical surface from ideally smooth or sphere surface, is described as error in smoothness (prism), or focus (lens). Error in smoothness or focus is often called error in contiguity because it is identified as a result of additional work on incumbency contact of control surface and optical element. Considering the fact that in this occasion interference stripes or rings appear, error in smoothness or focus is also called the error in colour. Mark for tolerance of contiguity contains number 3 and values of form

A (B) C

where:

A - limit for maximum number of allowed m varieties,

B - limit value for maximum Δm difference between these numbers in 90° different directions if the error in contiguity is even and

C - value for allowed fine error in F contiguity, deviations of rings from circular shape. Deficiency of limit value is marked with (-)

During processing of optical elements, beside previously mentioned, errors appear that causes loss of light, dissipation or reflection. These disturbances or fine surface structure are called **surface errors** and can be divided as: scratch, scrapes, spots, stains and whiskers. **Spots** are mainly dark places on the surface caused by entering of the polishing material into bubbles and rents that is caused by bad material characteristics. **Hair line** and **sleek** are surface errors that appear during polishing, wash or control, caused by recklessness or impure washing substances. **Crack's** and **crazing's** are roughly damaged sections caused by ragging of the material during machining or due to grinding residues entering the machining process. **Scratches and scrapes** results from the optical material cracking or from significant mechanical impact at the crack spot. Surface errors are labeled by

$$5 / (A \times S)$$

where:

5 – label for surface errors,

A – phase number and

S – cross-sectional intersection of surface errors.

Stress errors have negative influence on transmission of optical system and are caused by change of refraction index. Stress in optical material can be determined by photo-stress constants.

Beside errors in material and machining it is necessary to determine tolerances of shape and dimensions of optical elements. It is also necessary to determine optical functions of the elements that are much more variable and are not implied in standard classifications. For example, spectral characteristics vary from law reflections, mirror characteristics up to the total reflection of active optic surface.

8. CONCLUSIONS

By perceiving development of the programs for design, analysis and optimization of optical devices, it is possible to anticipate directions of its further development. In the next few years, there is a significant probability that the designer of the optical devices will not be an expert whose specialization is optical system design as now, but will be engineer with specialization in some other area that uses optical system in order to solve some specific technical problem. Common trend is that large number of specialized programs are used by not enough qualified designers – engineers. In the next years, programs for design of optical systems will be more tightly connected with CAD/CAM systems and with machines for production. Time necessary for design and production of optical system that comprises conceptual solution, analysis and optimization of the system, mechanical design and prototype production will shortened from a time measured by months to a time measured by days and maybe even hours.

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