Розроблено спеціальне програмне забезпечення для імпорту результатів кінцево-елементного аналізу оптичних систем у програми оптичного аналізу. Використання розробленої програми в комплексі з програмами кінцево-елементного та оптичного аналізу дозволяє дослідити вплив зовнішніх факторів (сил, температури) на якість зображення, що формується оптичною системою. Використовуючи розроблену програму, було досліджено полегшення позаосьових сегментів осесиметричних дзеркал

Ключові слова: поліноми Церніке, кінцево-елементний аналіз, оптомеханіка, моделювання навантажень, полегшення дзеркал

Разработано специальное программное обеспечение для импорта результатов конечно-элементного анализа оптических систем в программы оптического анализа. Использование разработанной программы в комплексе с программами конечно-элементного и оптического анализа позволяет исследовать влияние внешних факторов (сил, температур) на качество формируемого оптической системой изображения. Используя разработанную программу, было исследовано облегчение внеосевых сегментов осесимметрических зеркал

Ключевые слова: полиномы Цернике, конечно-элементный анализ, оптомеханика, моделирование напряжений, облегчение зеркал

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DEVELOPMENT OF SOFTWARE FOR COMBINING FINITE ELEMENT AND OPTICAL ANALYSES

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1. Introduction

In the process of developing numerous optical systems of aerospace purpose, it is necessary to take into account deformations that arise in the optical and mechanical elements of the structure. Such deformations can appear under the influence of vibrations, impacts, temperature and other factors. Taking into account deformations taking place during development of the systems will enable prediction of influence of external factors on the final optical image quality. This issue is especially relevant in the development of high-quality optical systems, for example, systems for remote Earth sensing from outer space, since designing and manufacturing such systems is costly. For such systems, it is important to take into account as much as possible the risks that can affect the image quality, even at the development stage.

To date, there is a large number of computer programs for finite-element analysis (for example, SolidWorks, Ansys, etc.) which help analyze influence of external factors on the system under study. Such computer simulation can significantly reduce cost and time of development of arbitrary systems. However, such programs do not provide for the possibility of optical analysis (image quality study) and import of the calculation results into specialized optical programs.

2. Literature review and problem statement

During simulation of elements of optical systems for remote Earth sensing scanners, developers mainly use the following basic types of analysis [1, 2]:

1) frequency analysis for determination of the first natural frequencies of oscillation of optical and mechanical components;

2) mechanical analysis for study of garavity force and other forces;

3) temperature analysis, that is, analysis of the temperature gradient within the optical components which is formed under the influence of external factors;

4) combined analysis, that is, mechanical analysis taking into account a change in the size of components under the influence of temperature gradients.

The first type of analysis can be practically completely carried out in the finite-element analysis programs. Other types of analysis also require the use of finite-element analysis programs. However, the results of this analysis (in the form of displacement of nodes of the component grid or temperature values in them) cannot be directly imported into the programs for optical analysis. Because of this, the quality study of the image formed by deformed components is a very difficult task.

There are some programs (for example, COMSOL Multiphysics) in which it is possible to conduct a comprehensive analysis of the influence of external factors on optical characteristics [3]. However, capabilities of such software are limited.

Very few specialized programs have been created to import finite-element analysis results into optical analysis systems. One such program is SigFit. This software package enables linking of finite element analysis performed in MD Nastran [4] or ANSYS Workbench [5] software with optical programs. The software package allows users to import the results of simulation of specific systems, such as diffraction gratings [6], large segmented mirrors [7], adaptive mirrors [8], etc. into the optical analysis programs. It uses a fairly complex mathematical apparatus based on the calculation of birefringence, which arises in the material of components under the influence of external factors [9]. Such an analysis is important for the systems in which polarization of radiation and shape of the wave front are critical [9].

But for most systems, polarization and shape of the wave front are not critical. For such systems (for example, remote Earth sensing systems), it is possible to create a simpler algorithm for calculating deformations, which will not be inferior to the accuracy of the algorithm based on the birefringence calculation.

3. The aim and objectives of the study

This work's objective was to develop specialized software for importing results of the finite element analysis into modern commercial optical analysis programs with the possibility of further system study.

To achieve this goal, the following tasks were solved:

– definition of input data to be generated by the finite element analysis program as a result of the study;

– development of a computing tool that will make it possible to evaluate deformation of the working surfaces of optical components under mechanical and/or thermal effects and to determine their numerical parameters suitable for evaluation in available optical analysis programs;

– checking working capacity of the developed software in studying ways of lightening axisymmetric and extraaxial segments of axisymmetric mirrors;

– definition of application field of the developed software.

4. Input data and algorithm of software operation for evaluating working surface deformations in optical components

To automate the procedure for analyzing surface deformations caused by mechanical and thermal factors, a special computer program Deform was developed. Its main window is presented in Fig. 1, 2 for different modes of operation. The program enables determination of numerical parameters (form, orientation and attitude) of the deformed surface and/or change of the refraction index in the component material caused by the gradient of volume distribution of temperature and load. Next, the obtained results can be exported to the present-day software of optical system calculation for further analysis of the obtained image quality.

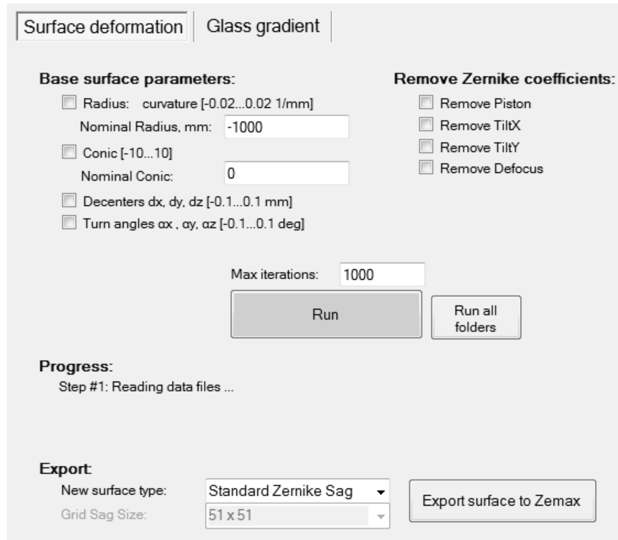


Fig. 1. Main window of the Deform program (in a Surface Deformation mode)

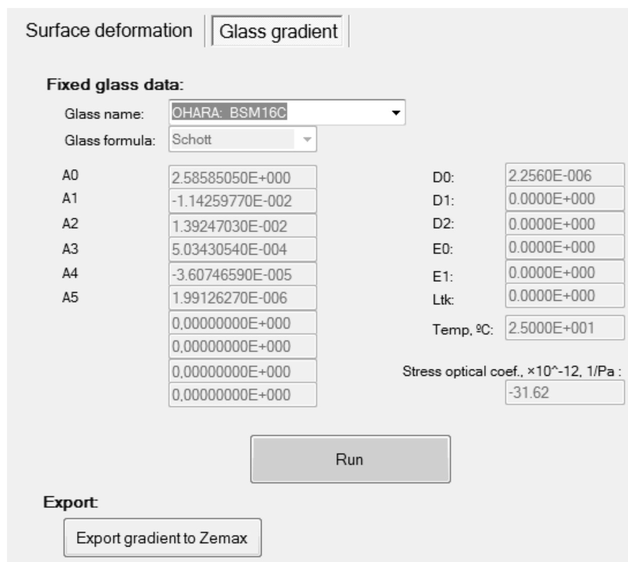


Fig. 2. Part of the main window of the Deform program (in the Refractive Index Gradient mode)

The main input data for calculation include the following:

– a subdirectory with files created with the help of the ANSYS Workbench software:

a) DEFORM.CSV or DEFORM_T.CSV file containing information on the surface deformation (in three Cartesian axes) caused by mechanical and thermal factors, namely, the coordinates of the model grid nodes before and after deformation;

b) TEMP.CSV file containing temperature values in each grid node of the three-dimensional model;

c) STRESS.CSV or STRESS_T.CSV file containing numerical values of pressure (in MPa) in each grid node of the three-dimensional model;

– optical parameters of the employed material (glass name, type of formula for calculating the refractive index, dispersion coefficients, thermal coefficients, optical strain coefficient);

– orientation of the cartesian axes of the model (choose one of the six available; XYZ by default);

– operating wavelength (0.6328 μm by default);

– the maximum number of iterations of the search algorithm (100 by default).

The general idea is to determine parameters of the shape and spatial orientation of the spherical or aspherical «basic» surface, which is most close to the deformed surface for a given set of surface points. Next, approximation of the deformation function of higher order is carried out. The developed models of the base surface are presented in Table 1.

Table 1

Available models of the base surface and their parameters

No.	Model type	Optimization parameters: Curvature	Conical, constant	Decentering to: X	Y	Z	Slope to: X	Y	Z
1	Centered spherical	+							
2	Decentered spherical	+		+	+	+			
3	Spatial spherical	+		+	+	+	+	+	+
4	Centered aspherical of second order	+	+						
5	Decentered aspherical of second order	+	+	+	+	+			
6	Spatial aspherical of second order	+	+	+	+	+	+	+	+

In such a statement, the problem is nonlinear and analytically insoluble. However, the search for the base surface can be effectively performed in an iterative way using one of the known methods of global optimization.

A classic differential evolution (DE) algorithm was used, which is a simple and heuristic algorithm [10]. In fact, DE is a powerful stochastic search method for solving global optimization problems based on genetic algorithms. Effectiveness of DE and its modifications has been successfully demonstrated in many application fields including image recognition, communication, mechanical engineering, etc. [11–16].

Action of DE can be described in brief as follows. At the beginning, a certain set of vectors is generated randomly, the so-called generation, which is evaluated by utility function (evaluation function). Then the next iteration process is repeated until the condition of termination is fulfilled. The main operators of DE are mutation, crossover and selection. The process of mutation in each generation begins by random selection of several (usually three) vectors in the population. Based on the selected vectors, the perturbed (mutant) vector can be created according to various schemes. In this case, DE/rand/1/bin scheme was used. Crossover operation is employed to the perturbed vector and the current vector of the population which results in a trial vector. The trial vector replaces the current vector in a case if the evaluation function is improved in it. In the opposite case, the current vector remains and is passed to the next iteration of the algorithm.

Residual deformations of higher orders are approximated by a surface represented by classical Zernicke polynomials (Fig. 3, *a, c*). Coefficients of decomposition of the surface deformation, which characterize the constant component, X and Y slopes as well as defocusing can be easily excluded from further analysis independently of each other. In real systems, such components can be eliminated by adjustment (Fig. 3, *b, d*).

The final report contains information on the found optimization parameters, which determine geometry and spatial orientation of the selected base surface, the numerical parameters of residual deformations of the higher order as well as the coefficients of decomposition of Zernicke polynomials (total of 36 coefficients for seven orders). The standard deviation (RMS) and peak-to-valley (PTV) height for a surface described by polynomials of high order are estimated before and after approximation. In order to control adequacy of the surface description, the report contains absolute maximum and root-mean-square errors of approximation.

For an example, Fig. 3 shows a false-color map of residual deformations of higher orders.

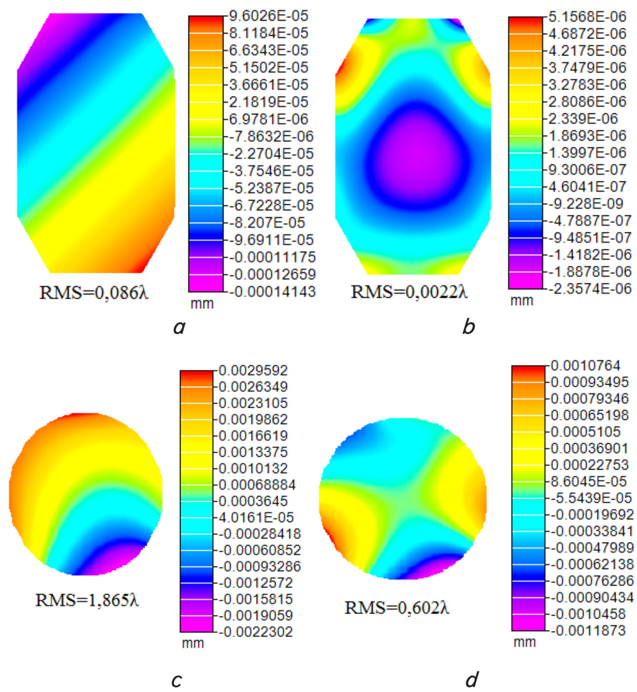


Fig. 3. An example of the obtained deformation of higher orders of the working surface of optical components of various shapes subjected to the action of mechanical force (the surface shape is determined by a set of specified points of the surface): all Zernicke coefficients are taken into account (*a, c*); the first four coefficients are excluded from the calculation (*b, d*)

For the optical surface that is analyzed, the working zone is specified. The working zone profile is determined by a set of specified surface points that have been imported from the ANSYS Workbench program. In addition, the program notifies the user in the case of potential errors: incorrect or missing data file(s), inability to estimate the base surface, etc.

The results obtained can be exported to a file with description of the optical system for further analysis in ZEMAX optical analysis software. The current version supports two types of deformed optical surfaces: Zernicke Standard Sag and GridSag with various numbers of grid points (grid size).

Gradient 4 surface can be applied to ZEMAX to approximate the glass refractive index changes resulting from temperature or mechanical factors. For each node of the grid, depending on the material used, refractive index of material is evaluated by applying the value of temperature or stress. The program supports catalogues of materials from leading manufacturers and known formulas for calculating refraction index (Schott, Sellmeier, Herzberber, Conrady, etc.).

A set of linear equations for unknown coefficients of the gradient model is available for the mentioned Gradient 4 model. Therefore, unlike the case of estimating the surface deformation, the refractive index gradient estimation can be achieved using the least squares method.

5. Results obtained in the study of lightening mirrors using the developed software

With the help of the software presented in this paper, ways of reducing weight of extraaxial segments of axisymmetric mirrors of a three-mirror anastigmatic quasi-orthoscopic lens were studied [17, 18].

Its optical scheme containing the undermentioned main components is presented in Fig. 4:

1) extraaxial segment of an axisymmetric hyperbolic concave mirror;

2) axisymmetric hyperbolic convex mirror;

3) extraaxial segment of an axisymmetric elliptical concave mirror;

4) flat mirror (to reduce the lens size).

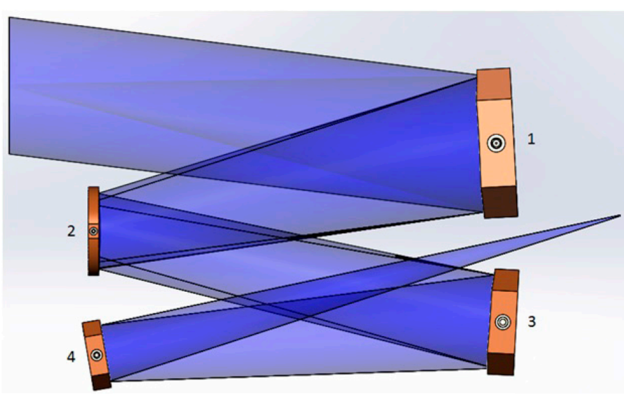
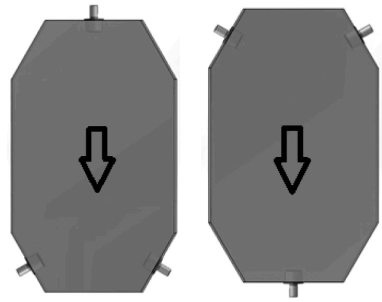


Fig. 4. Optical scheme of a three-mirror anastigmatic quasi-orthoscopic lens

During the study, a slightly modified version of mounting was used in comparison with that presented in [19]. Each mirror has 3 orifices with their axes in the same plane and intersecting at a common point within the mirror plane. A bushing is glued into each orifice. Hinges inserted inside the bushings are further fixed to the mirror frame. Each individual hinge can move freely in its bushing and when three hinges are used, the mirror is secured in the desired position. The considered mounting option not only provides for a temperature «isolation» and does not cause additional deformations but also provides a simple mechanism for adjusting each mirror in the lens.

The whole analysis was carried out with two mounting options: two hinges at the mirror bottom side (Fig. 5, *a*) and two hinges at the mirror top side (Fig. 5, *b*). The mirror takes an upright position. The force of gravity acts in the direction of the arrow in Fig. 5.



a *b*

Fig. 5. Fastening of the mirrors: *a* — two hinges at the mirror bottom side; *b* — two hinges at the mirror top side

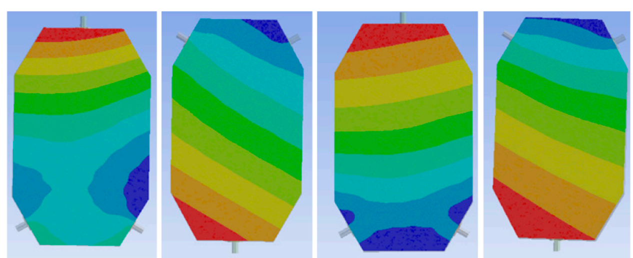
Two options of weight reduction were considered: with the back wall and without it [20].

The orifices were of various shapes: hexagonal, square, round and triangular.

After selection of the fastening option and the mirror material, geometric parameters of weight reduction were optimized. The number of orifices, their location and thickness of the ribs between the orifices were varied in the process of optimization. Options with the back wall and without it, variation of diameters and depths of the orifices have been also considered. More detailed information on this study is presented in [21].

Values of root-mean square (RMS) surface deviation were calculated with the help of the DEFORM program for each option selected for study. It was this criterion that was used in selection of the best option of weight reduction.

Fig. 6 shows some calculated RMS values obtained in simulation.



a *b* *c* *d*

Fig. 6. Deformation of the first mirror in different mounting variants with weight reduction: weight reduction without the back wall, 2 hinges at the botton side (RMS=0.0218λ) (*a*); weight reduction without the back wall, 2 hinges at the top side (RMS=0,0130λ) (*b*); weight reduction with the back wall, 2 hinges at the bottom side (RMS=0,0135λ) (*c*); weight reduction with the back wall, 2 hinges at the top side (RMS=0,0039λ) (*d*)

As can be seen from Fig. 6, the mirror is compressed in the mounting variant when two hinges are at the bottom side and tensioned when two hinges are at the top side. As it can be seen from the calculated RMS values, the mounting option with two hingeson at the top side in combination with the back wall ensures smaller deformation of the working mirror surface.

As a result of modeling in ANSYS Workbench program and calculating RMS in DEFORM program, the type of weight reduction and fastening and the geometric parameters enabling achievement of the smallest deformation of the working mirror surface were determined.

5. 1. Import of the results obtained in the finite element analysis into the programs for optical analysis and evaluation of the modulation transfer function

The next step in the development of lightweight mirrors is testing quality of the images they form in the terrestrial conditions. The modulation transfer function (MTF) for an ideal lens calculated in the software package for optical analysis is presented in Fig. 7

The MTF graphs shown in Fig. 8 were obtained in ZEMAX optical analysis program for a lens with three nonlightened mirrors deformed under action of the gravity force. These graphs were obtained after importing simulation results from ANSYS Workbench using DEFORM program. The mirrors were placed as shown in Fig. 5, *b*. As can be seen from the graphs, the greatest deterioration in the image quality was observed at the edge of the field of view due to stretching of the mirror under the influence of gravity.

Fig. 9 shows MPF graphs for a lens with mirrors deformed under the action of gravity with the chosen version of weight reduction. The mirrors were placed in a similar manner (Fig. 5, *b*) but the overall weight was decreased when lightening procedure was used and thus stretching of the parts became smaller.

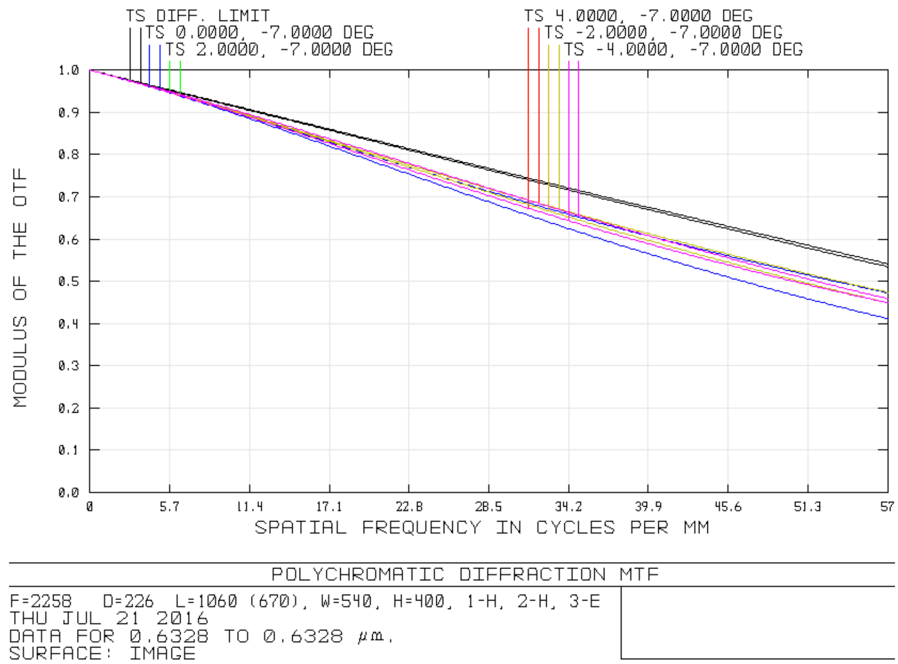


Fig. 7. The ideal lens MTF

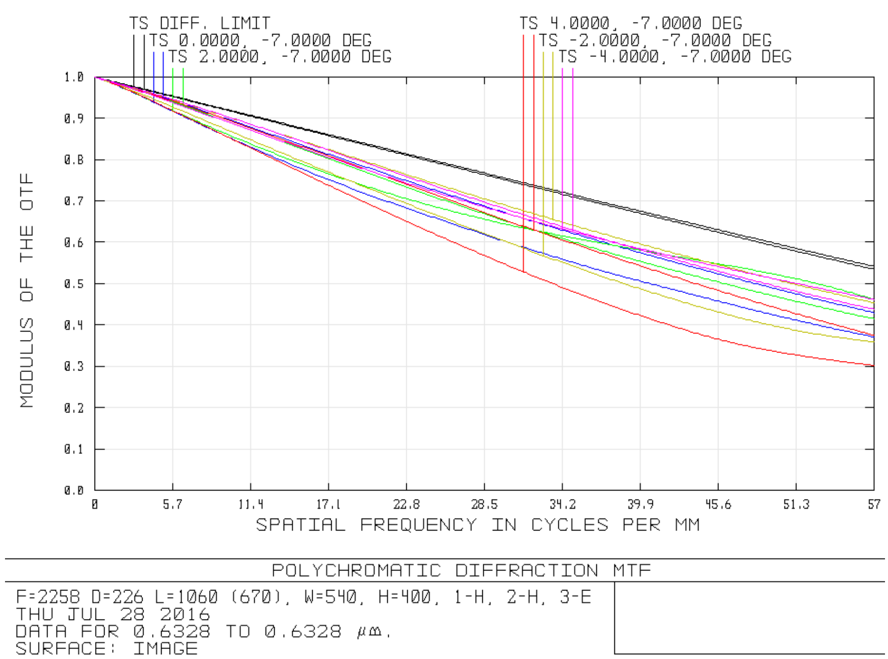


Fig. 8. MTF of the lens with deformed nonlightened mirrors

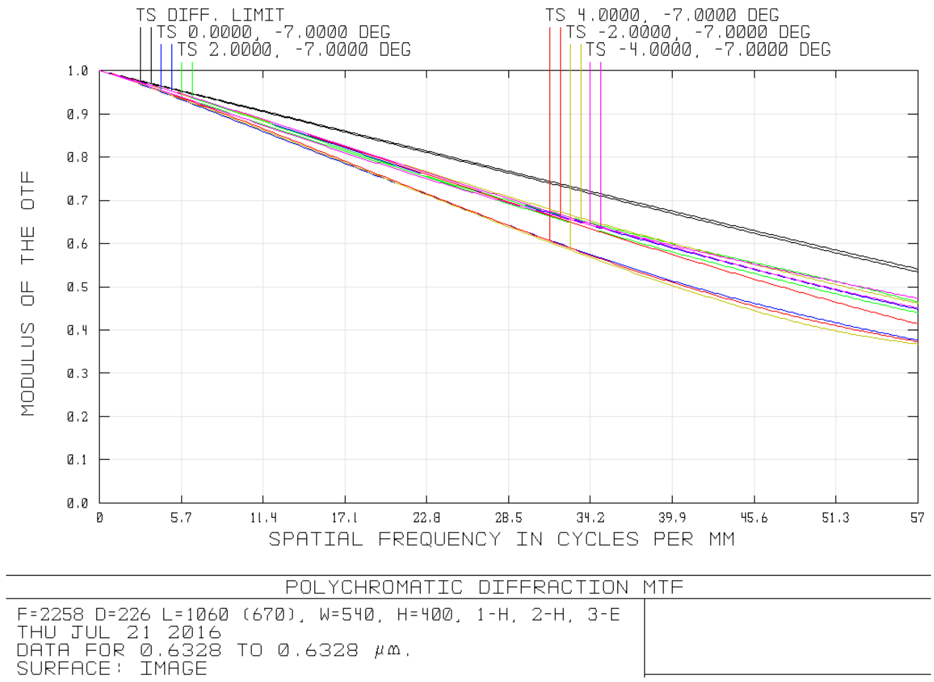


Fig. 9. MTF of the lens with deformed lightened mirrors

As a result, the system MTF at the edges of the field of view has improved considerably when lightened mirrors were used.

6. Discussing potentials of application of the developed software and the results of mirror lightening

The developed software enables import of the results of static, temperature, and combined simulation carried out in ANSYS Workbench into ZEMAX program for optical analysis. Use of this software makes it possible to estimate quality of the images generated by optical systems under coditions of action of external factors (forces and temperatures). This allows one to reduce number of field tests needed to develop a system and reduce their time and cost.

The software under consideration additionally has the function of calculating deformation values for the optical component working surface in a parametric study carried out in ANSYS Workbench software environment. Following the calculation of surface deformation for any number of points under study, Deform program calculates standard RMS deviation for each point. Next, the program produces information in a tabular form. This makes it possible to optimize parameters of the optical system and its components to minimize deformation.

Operability of this software has been proven during development of means for lightening the three-mirror anastigmatic quasi-orthoscopic lens. With the help of parametric modeling, a study was carried out on the influence of geometric parameters of weight reduction and fastening on deformation of the working surface of extra-axial segments for axisymmetric mirrors. As a result of this study, the option of lightening and fastening was used which minimized deformation of the working surfaces of mirrors. Next, the results of simulation of gravity force impact on the mirror which was carried out in ANSYS Workbench were imported into ZEMAX optical analysis program for obtaining MTF charts of the system.

As a result of application of the developed software, we have managed to reduce weight of the optical system from about 20 kg to 14 kg, that is, weight reduction was 30 %. Use of lightweight mirrors made smaller deformation of their working surfaces which improved MTF in comparison with nonlightened mirrors.

It is worth noting that due to the fact that approximation of the surface deformations was performed with the use of Zernicke coefficients which are determined in a unit circumference (Fig. 10), errors in estimation of root-meen-square deviation can appear during calculation of non-round surfaces.

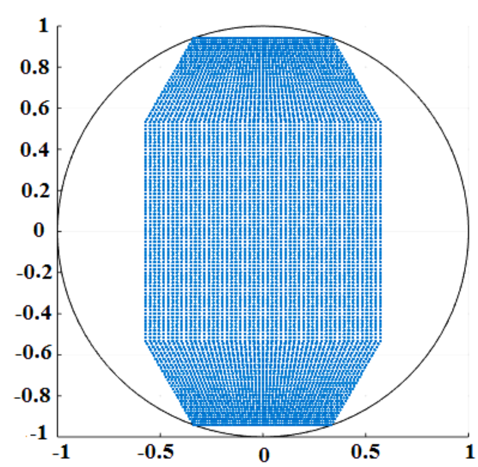


Fig. 10. Unit circumference and the mirror for which deformations were calculated

It was established that the narrower the mirror, the greater errors, especially at the part edges. However, these errors have little effect on the result obtained in calculation of mirrors with a smaller to a bigger side ratio more than 0.4.

If this ratio is less than 0.4, application of this program is not recommended since this error increases and begins to affect the calculation results. When calculating the temperature gradient, there are no restrictions on the surface shape.

7. Conclusions

1. Search for the parameters necessary for functioning of the algorithm of deformation assessment was carried out. These parameters are the coordinates of the model grid nodes before and after action of deformations and/or temperature in each grid node. This dataset should be generated by a program for finite element analysis. It is also necessary to specify the working wavelength, orientation of the model cartesian axes and the optical parameters of the material (for thermal study).

2. An algorithm was developed to evaluate deformation of the working surfaces of optical components under the influence of external factors. The general idea is to determine parameters of the shape and spatial orientation of the spherical or aspherical «basic» surface which is most closely approximated to the deformed surface for a given set of surface points. To do this, one of the methods of global optimization, an algorithm of differential evolution, was used. Approximation of the deformation function of higher order was then carried out. On the basis of the created algorithm, a program for automation of calculations was developed. Unlike other programs in which the course of each beam is calculated, this program immediately finds position of the entire surface greatly reducing calculation time. The developed program also enables determination of the numerical deformation parameters for further transfer of these data to the optical analysis programs for estimating MTF of the systems with deformed components.

3. Performance of the developed program was checked during the study of ways of lightening axisymmetric and extra-axial segments of axisymmetric mirrors. With the help of the developed program, we have managed to reduce weight of optics by 30 % and improve MTF of the system in comparison with the system without weight reduction.

4. The program makes it possible to calculate plane, spherical and aspherical surfaces of the second order. According to the results of the study, limitations in the work of the developed program for determining deformation of non-circular surfaces were found. Beacause of the use of Zernicke polynomials for approximating deformation of the higher order in calculation of optical surfaces with the smaller to bigger side ratio less than 0.4, the program cannot be used. When calculating deformation of round surfaces and temperature gradients for any surfaces, there are no restrictions.

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DESIGN OF FIRE DETECTORS CAPABLE OF SELF-ADJUSTING BY IGNITION

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Сформульовано критерій оптимізації самоналагоджувальних сповіщувачів. Розроблено алгоритми та структура таких сповіщувачів. Їх відмінною рисою є можливість ефективного застосування в невизначених умовах для довільних і заздалегідь невідомих горючих матеріалів. Верифікація запропонованих сповіщувачів свідчить про їх здатність забезпечувати раннє гарантоване виявлення осередків загорянь різних матеріалів в заздалегідь невідомих умовах

Ключові слова: самоналагоджувальний пожежний сповіщувач, гарантоване виявлення загоряння, горючий матеріал, порогове значення, верифікація

Сформулирован критерий оптимизации самонастраивающихся извещателей. Разработаны алгоритмы и структура таких извещателей. Их отличительной чертой является возможность эффективного применения в неопределенных условиях для произвольных и заранее неизвестных горючих материалов. Верификация предложенных извещателей свидетельствует об их способности осуществлять раннее гарантированное обнаружение очагов загораний различных материалов в заранее неизвестных условиях

Ключевые слова: самонастраивающийся пожарный извещатель, гарантированное обнаружение загорания, горючий материал, пороговое значение, верификация

1. Introduction

More and more attention is paid today to creating self-learning fire detectors (FD) for the systems of automated fire-prevention equipment (SAFE), capable of adjusting to fuzzy and changing operating conditions. For such conditions, it is impossible to design in advance the optimal SAFE with predetermined parameters [1, 2]. Actual statistics of loss-causing fires testify to the fact that operating conditions of SAFE on modern sites are varied and unpredictable. In this regard, designing the SAFE with predetermined parameters, which would provide their guaranteed fire protection, is not feasible.

The main information source on the ignition on sites for SAFE are FD. Contemporary FD generate information about ignition based on various physical components of combustion [3]. Great requirements to the ignition detection are put forward to thermal FD, which are widely used in various early detection systems when initial dynamics of growth of ambient temperature is considerably disguised by random thermal disturbances. That is why it is becoming increasingly important to create self-learning thermal FD, capable of improving their functioning, providing guaranteed detection of an ignition source under various and unpredictable conditions of using diverse flammable materials.