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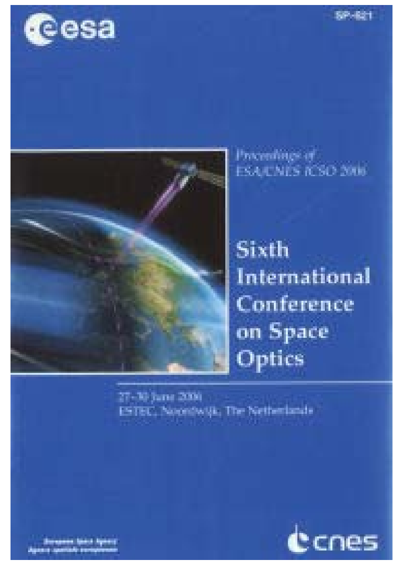

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INTEGRATING OPTO-THERMO-MECHANICAL DESIGN TOOLS: OPEN ENGINEERING'S PROJECT PRESENTATION

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ABSTRACT

An integrated numerical simulation package dedicated to the analysis of the coupled interactions of optical devices is presented. To reduce human interventions during data transfers, it is based on in-memory communications between the structural analysis software OOFELIE and the optical design application ZEMAX. It allows the automated enhancement of the existing optical design with information related to the deformations of optical surfaces due to thermo-mechanical solicitations. From the knowledge of these deformations, a grid of points or a decomposition based on Zernike polynomials can be generated for each surface. These data are then applied to the optical design. Finally, indicators can be retrieved from ZEMAX in order to compare the optical performances with those of the system in its nominal configuration.

1. INTRODUCTION

For a growing number of applications having to perform in demanding conditions such as space instruments optics (telescopes, optical benches, etc), fibre optics or optical Microsystems (MOEMS), the need for high dimensional stability, increased accuracy and predictable performances raises the standards for the design of optical devices. In most cases, the use of computer-based design approaches for optical devices is growing.
However, from telescopes to optical fibres, a more integrated optics (and mechanical, thermal, …) analysis is required for design in laser applications, MOEMS, optical computers, biomedical camera or implants, injected micro prisms, optical switches, etc. While separated applications exist to perform individual analyses for both optical and structural behaviours, an integrated software solution allowing a coupled analysis of these interactions in the same environment is still lacking. Based on the same parametric geometry, such a tool would not only allow consistent accurate formulations and design flow, but also open the door to coupled design optimisation.

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Open Engineering is developing such an integrated numerical simulation tool which will allow analysing coupled interaction between the optical behaviour and its structural medium due to mechanical or thermal solicitations. In this first stage, the resulting application will be an enhancement to the existing OOFELIE® software to enable the dialogue with the optical simulation software ZEMAX®, offering the ability to exchange the geometry of optical surfaces, material properties and results associated between the codes, mainly through direct in-memory dialog. The whole is embedded in a consistent pre-post graphical user interface which includes parametric model management.

2. PROJECT'S GOALS

This project, which benefits from a partial funding from ESA, has several objectives.
A first goal mainly consists in the introduction into OOFELIE of in-memory dialogue capabilities enabling the exchange of information with ZEMAX to reduce human interventions during data transfer between the two applications, thereby gaining productivity and reducing risk of loss of data integrity.
The major goal is the automation of the improvement process of an existing optical problem with structural deformation related information. The initial definition of a given optical surface is enhanced with the definition of grid sag values or coefficients from a Zernike polynomials decomposition.
The final goal of these developments consists in allowing parametric analyses in the design to search for a near-optimal optical design according to perturbations introduced by thermo-mechanical solicitations on its structural support.

3. COMMUNICATION MODEL

The general design procedure of an optical device starts with the generation of the optical design. In this project, the optical analysis software is ZEMAX. In a second stage, the thermo-mechanical design is performed. The creation of the model is performed in the SAMCEF Field graphical user interface while the solution is computed by OOFELIE's resolution methods.

Using information related to this mechanical problem, the initial optical design within ZEMAX could be enhanced in order to compare its optical performances with the nominal one. A frequent enhancement consists in the description of the deformation of the surface of an optical entity using either a grid of points or as a linear combination of Zernike polynomials.
So, information must be exchanged between OOFELIE and ZEMAX. OOFELIE is going to add data in the description of ZEMAX's surface and is going to retrieve optical indicators from ZEMAX.
Dynamic data exchange (DDE) is a powerful feature of the Microsoft® Windows operating environment. DDE provides a protocol through which applications can exchange data of all sorts. DDE always occurs between a client application and a server application. The DDE client application initiates the exchange by establishing a conversation with the server to send transactions to the server. A transaction is a request for data or services. The DDE server application responds to transactions by providing data or services to the client.
OOFELIE has been adapted to play the role of the DDE client as ZEMAX can play the role of the DDE server.
This mode of communication between OOFELIE and ZEMAX reduces human interventions during data transfers between the two applications.

4. VIRTUAL MOCKUP

Since OOFELIE::OptoThermalMeca is completely integrated into the SAMCEF Field graphical user interface, all the analysis steps (from geometric model definition to results visualization) are performed in the same environment. Using the same environment to perform all these steps helps the designer a lot and avoids mistakes due to data transfers between applications. The five analysis steps are:

4.1 Geometric model definition

In this module, the geometric model is built. It can be directly generated using classical CAD capabilities (sketches creation, extrusion, Boolean operations, etc) or it can be imported from a standard CAD format (IGES, STEP, BREP, CATIA, etc).
For optical problems defined with ZEMAX, lenses can be imported using either the STEP or IGES format. The consequence is that, in the mechanical problem, optical surfaces are positioned in the same way as in the optical design because ZEMAX's exportation tool works in this way. Both designs are thus sharing the same geometry. This mode of description of optical surfaces in the mechanical problem is favoured as it avoids the introduction of a lens editor in the geometry module of SAMCEF Field.

4.2 Data application

In this second module, data are directly applied on the geometry. For example, behaviours and materials are applied on solid entities while boundary conditions such as clamps or prescribed temperatures are applied on faces.
For optical problems, some surfaces could be identified as optical ones because, later in the process, OOFELIE will need to know which nodes of the finite element model belongs to a particular optical surface. This identification is going to enable OOFELIE to generate either a grid or a set of Zernike coefficients to describe the deformed state of the surface due to a thermo-mechanical solicitation.
Fig. 1 presents the dialogue box where the user specifies the type of an optical surface, its aperture and the position of the same object in the lens editor of the associated ZEMAX problem. In this case, the mirror presents a rectangular aperture and the coefficients of the Zernike decomposition using Fringe Zernike polynomials are going to be computed after the thermo-mechanical simulation.

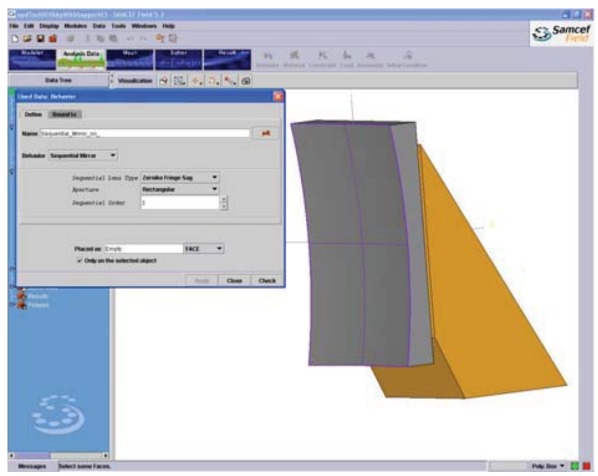

Fig. 1. Dialog box for sequential lens's property.

Table 1 presents, for this mode of operation where OOFELIE is used to update an existing optical problem defined in ZEMAX, the types of optical surfaces the user can apply in the mechanical problem according to the working mode of ZEMAX.

Table 1. Surface types in updating mode.

Type of surface	Sequential ZEMAX Mode	Non Sequential ZEMAX Mode
Standard Zernike polynomials	Available	Available
Fringe Zernike Polynomials	Available	Does not exist in this mode
Grid Sag	Available	Available soon

4.3 Meshing

Next, the meshing of the geometric entities can be performed. Note that SAMCEF Field offers a complete solution of meshing algorithms (mesh length specification, non-uniform distribution, linear & quadratic elements, etc).

4.4 Solver call

Then, the OOFELIE solver is called to compute the results. If some parameters need to be specified before the solver call, they are introduced in this module.
For optical problems, the user is able to specify the name and location of the corresponding ZEMAX problem file. So, OOFELIE is going to be able to load that file within ZEMAX and perform data transfers with this application.
The generation of the mechanical design is an iterative task. During these iterations, the updating process of the ZEMAX problem may not be necessary. So the user can deactivate the ZEMAX connection in the resolution scheme by choosing not to activate the ZEMAX connection and still be able to perform thermo-mechanical analysis of the studied problem.

4.5 Results visualization

Finally, the results can be visualized using SAMCEF Field which offers all the functionalities that designers need for the interpretation of FEM results (3D & 2D displays, etc).
The post processing of optical results is also present. If available from the ZEMAX problem, optical rays and values of the merit function can be displayed directly inside SAMCEF Field. Fig. 2, for example, presents the structural model of a mirror and its support together with rays within the post-processing module of SAMCEF Field.

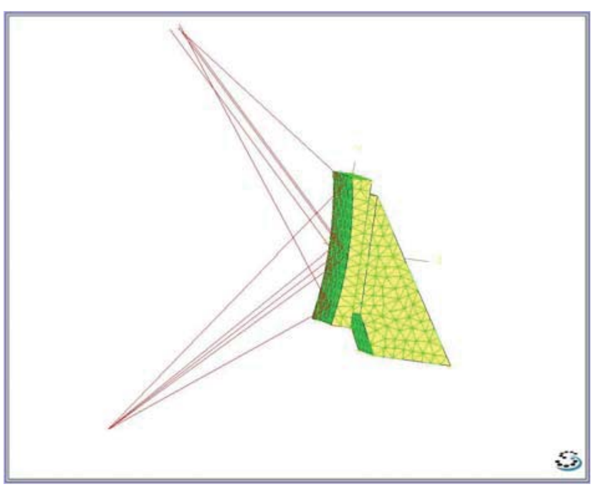

Fig. 2. Post-processing of optical rays.

5. THE TWO ANALYSES

With OOFELIE::OptoThermalMeca, two classical analyses are easily performed on the same model, from a simple change of definition of the solver to be called.

5.1 Linear Static analysis

A linear static analysis can be performed on a mirror. In this case, Eq. 1 corresponds to the matrix system resulting from a finite element modelling which is going to be solved.

$$\begin{bmatrix} \mathbf{K}_{uu} & -\mathbf{K}_{u\theta} \\ \mathbf{0} & \mathbf{K}_{\theta\theta} \end{bmatrix} \begin{bmatrix} \mathbf{u} \\ \boldsymbol{\theta} \end{bmatrix} = \begin{bmatrix} \mathbf{f} \\ \mathbf{q}_{\text{therm}} \end{bmatrix} \tag{1}$$

Fig. 3, for example, presents the temperature distribution generated by a heat flux applied to the surface of the mirror.

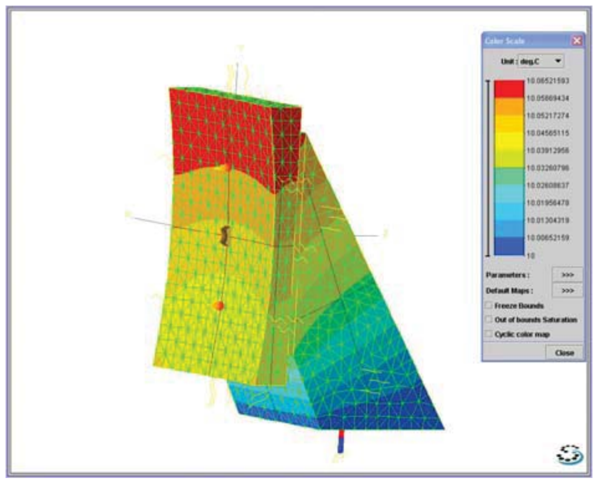

Fig. 3. Temperature and displacements fields.

5.2 Transient analysis

A transient response can be directly computed with OOFELIE. Here, Eq. 2 corresponds to the complete system

$$\begin{bmatrix} \mathbf{M}_{uu} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{u}} \\ \ddot{\boldsymbol{\theta}} \end{bmatrix} + \begin{bmatrix} \mathbf{C}_{uu} & \mathbf{0} \\ \mathbf{C}_{\theta u} & \mathbf{C}_{\theta\theta} \end{bmatrix} \begin{bmatrix} \dot{\mathbf{u}} \\ \dot{\boldsymbol{\theta}} \end{bmatrix} + \begin{bmatrix} \mathbf{K}_{uu} & -\mathbf{K}_{u\theta} \\ \mathbf{0} & \mathbf{K}_{\theta\theta} \end{bmatrix} \begin{bmatrix} \mathbf{u} \\ \boldsymbol{\theta} \end{bmatrix} = \begin{bmatrix} \mathbf{f} \\ \mathbf{q}_{\text{therm}} \end{bmatrix} \tag{2}$$

which has to be solved using a HHT algorithm [1].

For example, Fig. 4 presents the evolution of the temperature applied to the surface of the mirror while Fig. 5 presents the evolution of the displacement of a node of the mirror due to this variation of the temperature.

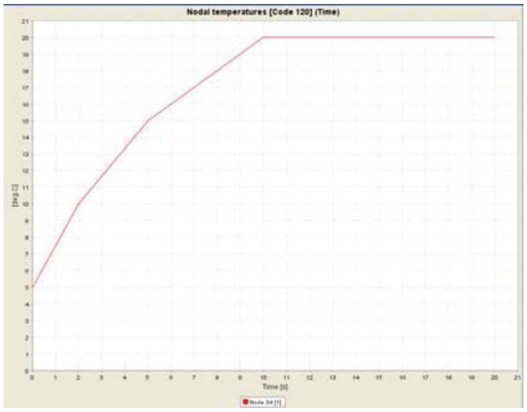

Fig. 4. Temperature vs time.

Fig. 5. Displacement vs time.

6. COUPLED SOLVER

Specific capabilities, adapted to the simulation of optical problems, have been introduced inside OOFELIE and are detailed hereafter.

6.1 Mesh improvement

The optical problem is described in ZEMAX and some of its optical surfaces are exported using a standard CAD exchange format (STEP or IGES). These files are then imported in SAMCEF Field to begin the creation of the structural problem.
But, optical surfaces containing aberrations such as even or odd aspheric surfaces may not be very accurately represented using standard CAD exportation exchange formats. Indeed most of the time such surfaces are represented using NURBS[1] curves and surfaces.
Often, operations between geometric entities (such as Boolean or cut operations) are changing the parametric description. These modifications can lead to a potential precision loss in shapes representation.
Once the geometry of the model has been created, it is meshed. During this operation the geometry can also be approximated by the meshing process. For example, curved geometries can be represented using linear elements.
The consequence is that the mesh's nodes might not be exactly on the initial geometry. This potential lack of precision can be problematic for optical systems where the allowed deformations must be close to 10 nanometres. For such cases, the initial geometry could be represented with an error of the same order of magnitude as the requested tolerance for the deformations.
As OOFELIE can extract information from ZEMAX and as each optical surface, in the mechanical problem, is linked to the same optical surface in the optical problem, OOFELIE can perform a verification process of the sag of each node of the mesh belonging to an optical surface. If the sag is not represented with a sufficient precision, OOFELIE can recompute its value using the analytical equation of the surface provided by ZEMAX thereby increasing the sag precision.
Fig. 6 presents the sag correction for an odd aspheric surface with a circular aperture.

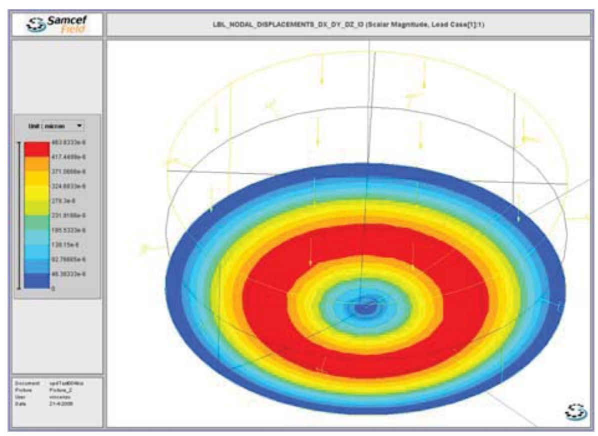

Fig. 6. Sag correction for an odd aspheric surface.

6.2 Generation of a Grid Sag

The deformation of an optical surface due to thermo-mechanical loading can be converted into a Cartesian grid of points loadable by ZEMAX. Each value of the grid represents the sag affected to the discrete point of the grid.

For each optical surface of the mechanical problem, OOFELIE can generate such a file. OOFELIE also automatically modifies the optical problem to:

1. Change the type of the surface to GRID SAG.

[1] NURBS=Non-Uniform Rational B-Splines

2. Load in the extra data editor of ZEMAX the generated grid file.

For each optical surface in the mechanical problem declared as Grid Sag, the user can specify the numbers nx and ny of points in each direction of the grid that is going to be generated.

6.3 Generation of Zernike coefficients

The deformation of an optical surface due to thermo-mechanical loading can be expressed as a linear combination of Zernike polynomials.
ZEMAX can deal with two families of Zernike polynomials: the Fringe [2] and the Standard [3] polynomials. These two families are also managed by OOFELIE.
For both families, OOFELIE can retrieve the coefficients of the combination following the methodology proposed by Malacara [4]. These coefficients are then automatically exported in ZEMAX's extra data editor.
When the surface's deformations are going to be expressed as a linear combination of standard Zernike polynomials, the user can specify the number of polynomials to use. If Fringe Zernike coefficients are to be used all the 37 polynomials are considered in the retrieving process.
Table 2 presents the seven first coefficients retrieved when the deformations are represented with Fringe Zernike polynomials.

Table 2. First computed coefficients.

Fringe polynomial number	Coefficient
1	-2.95324e-005
2	-9.80621e-008
3	-4.82057e-006
4	-3.06545e-007
5	-1.08925e-007
6	-3.12359e-010
7	-5.37026e-008

The retrieving process of Zernike coefficients is executed either at the end of the linear static analysis or after the determination of the transient response of the system.

7. CONCLUSION

It has been demonstrated that multiple analyses on thermo-mechanical systems can be easily performed using OOFELIE::OptoThermalMeca.

Extensions to OOFELIE, specifically targeted to the design of optical systems, have been presented as well as the close connection with the optical analysis software ZEMAX.

In order to increase the precision of the mesh's nodes belonging to optical surfaces, the sag of these nodes can be recomputed according to the analytical equation used by the optical design.
The deformation of the surface of optical entities can be translated into valuable information for ZEMAX. Either a grid of points or a set of coefficients used in a linear combination of Zernike polynomials can be generated.
The optical design can then be automatically updated using in-memory communication between OOFELIE and ZEMAX. Optical rays and indicators can also be retrieved from ZEMAX. These automated processes minimize the human interventions during the design phase and thus reduce the risk of loss of data integrity.
The fact that all the analysis steps are performed in the same environment is a great step forward in the modelling of opto-thermomechanical systems.

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