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SIMULATIONS FOR OPTICAL DESIGN AND ANALYSIS

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Abstract

Why should we apply optical simulation and light modeling software? More and more improperly designed low-grade products can be found on the market, which can cause negative experiences and financial losses both to the vendors and to the users. Incorrect prototypes or products always require re-design. The worse option is the re-manufacturing, which is extremely expensive. To avoid these problems, we can apply software for optical design and analysis, which is an economical solution. The prototype of the product will be properly designed, thus posterior modification or remanufacturing of the molding and forming tool is avoidable. The time of the design can be significantly reduced as well. A professional light-modeling and simulation software called OPTIS SPEOS is used at the BUTE - MOEI, to design and develop different optical and lighting systems. This paper describes some of our experiences with optical design and light modeling.

1. How can the optical-light modeling simulation software assist the designers?

The simulation environment can be created quickly and easily. Virtual sensors can be set in arbitrary position and theoretically in unlimited number. The results of the geometrical modifications can be checked immediately, which means direct feedback. High precision can be also achieved with detailed settings. The simulation results are spectacular, and the analysis is properly detailed. Virtual reality environment can also be used, if necessary (Abb 1).

Abb. 1: Generated virtual reality environment for windshield analysis [4]

2. Which industries apply these software?

Mainly, the automotive industry (for optical part design: lamps, mirrors, dashboard analysis, indicator lamps, etc.), the optical industry (design of optical products, components, lenses, etc.), indoor / outdoor lighting, and the mobile phone industry (Abb. 2). There are also applications in the aircraft industry (e.g. cockpit analysis, Abb. 1), and in the screen and display industry, and in traffic control (design and testing of traffic lamps) as well.

Abb. 2: Luminance analysis of mobile phone buttons [4]

3. Classification of modern optical simulation software

Modern optical simulation software can be divided into three sub-categories based on their used engine [1]:

1. ***Sequential ray tracing***: the algorithm substitutes the light source with directed rays, then guides these rays through the pre-defined optical elements in a determined order. Ray tracing is capable of simulating a wide variety of optical effects, such as reflection and refraction, scattering, and dispersion phenomena (such as chromatic aberration).

Boundary conditions specify the optical properties of the optical elements. This algorithm is ideal for lens system design.

2. ***Non-sequential ray tracing*** (e.g. SPEOS): the rays can reach one surface in multiple times and in any order. Ray scattering is allowed (e.g. part of the light reflects from a surface, one part absorbs, etc.). The order of the ray tracing is arbitrary. The algorithm is ideal at complex optical system design, where diffuse surfaces and scattering light occurs.
3. ***Finite-difference time-domain (FDTD)***: mainly used in the design of micro-optical systems, where there are optical elements at a size of the wavelength of light. The procedure calculates electromagnetic wave propagation with Maxwell equations, thus the wave-optical calculations can be obtained with high accuracy.

4. Mathematical background of SPEOS: Monte Carlo method

The algorithms applied by SPEOS are mainly confidential but based on the Monte Carlo method, what was coined by John von Neumann in 1947.

Using this method, deterministic problems can be solved with the sequence of random events. The software orders probability density functions for the unknown parameters. In contrast to the deterministic methods, due to the random sampling, the Monte Carlo method needs less calculation (computation), and less boundary condition to the geometries. Thus, simulation time is significantly shorter. For the evaluations, the software uses statistical estimation methods [2].

As a ray reaches a surface, its further path depends on the pre-defined optical properties, what the following equation (BRDF - Bidirectional Reflectance Distribution Function) [3] describes (Abb. 3):

$$f_r(\omega_i, \omega_0) = \frac{dL_r(\omega_0)}{dE_i(\omega_i)} = \frac{dL_r(\omega_0)}{L_i(\omega_i)\cos\theta_i d\omega_i} \quad (1)$$

ω_i - Vector directed to the light source, ω_0 - Vector directed to the observer (sensor), L – Luminance, E - Illuminance, i – Incoming parameter, r – Reflected parameter. θ – Angle between n, and the ray

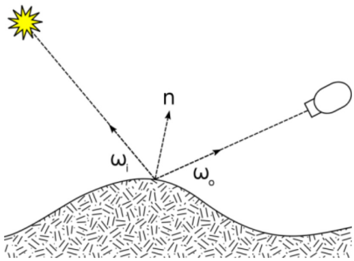

Abb. 3: Bidirectional reflectance of the surface

Such a function can be specified for all surfaces. In a photometric approach, BDRF defines the surface reflection in function of the illuminance and the observer's location. BDRF depend on the wavelength, as well as the structural and optical properties of the material. We can discuss about the BTDF (Bidirectional Transmittance Distribution Function) of the material, which defines the transmission properties [3].

5. Main steps of creating the simulation environment

5.1. Define geometries

The SPEOS simulation module works under CATIA V5, Pro/Engineer or SolidWorks environment, but it is available in Stand Alone version as well. Thus, the main CAD file types are compatible with SPEOS. Thanks to the complete integration, the data transfer between the simulation and the CAD software, which can cause errors, and makes the process slower and complicated is unnecessary.

5.2. Define light sources

In modern light sources, the manufacturer provides the luminous intensity distribution database files for the simulations, in international standard formats (e.g. Eulumdat, IES). This file contains all necessary information about the light source. The luminous distribution can be also specified with "Ray Files", which defines millions of guided ray vectors (Abb. 4). The software can calculate with these vectors quickly and easily. Of course we can implement measurement results as well, to achieve better accuracy.

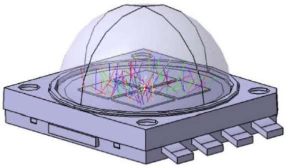

Abb. 4: LED light source with guided ray vectors at chips

5.3. Set material and surface optical properties

Due to the simulation accuracy, the optical property settings of materials and surfaces which are involved in the simulation, should be defined as precisely as possible. We can choose materials from the built-in or the downloaded database catalogues, but self-made or measured material properties can be used too.

We can define optical properties (e.g. reflection index, absorption, optical polished surface, transmission, scattering properties, etc.) to the complete bodies, or discrete surfaces (Abb. 5).

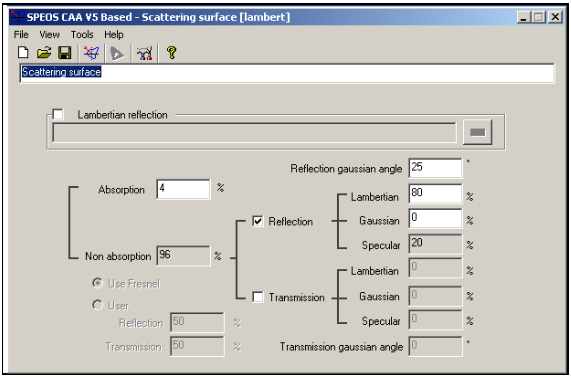

Abb. 5: An easy way to set surface optical properties

There are two possible ways to define optical properties (Abb. 6):

- „Volume optical properties (VOP)" : behavior of the light rays inside the body
- „Surface optical properties (SOP)" : behavior of the light rays as it reaches a surface

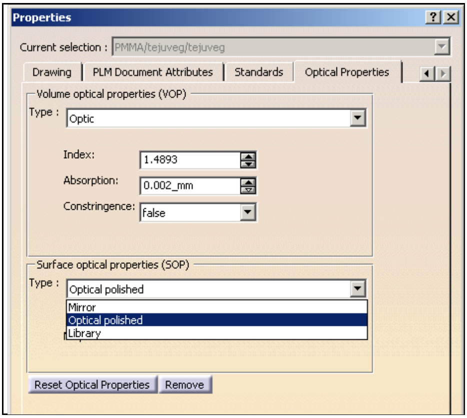

Abb. 6: Define VOP and SOP

5.4. Define sensors

Sensors are the virtual equivalent of real measurements, thus all photometric and radiometric quantities can be measured. Virtual sensors can be put everywhere and theoretically in unlimited number. For example we can define sensors in the middle of a solid body, which would be in reality impossible. The size (or shape), resolution, orientation, and of course the spectral sensitivity of the sensor can be defined according to the designer's claims. The most important sensor types can be seen below:

- Irradiance sensor – Illuminance [lm/m2 = lx] (or Irradiance [W/m2]);
- Radiance sensor – Luminance [cd/m2] (or Radiance [W/m2sr])

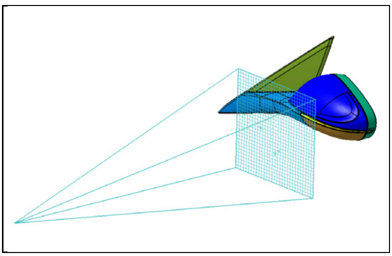

Abb. 7: Radiance sensor from a discrete view point

- 3D intensity sensor – Light intensity [lm/sr = cd] (or Radiation intensity [w/sr]);

The shape of the sensor can be spherical or hemispheric (Abb. 8). Luminous flux [lm] can be measured too, from any distances, which substitutes an integrating sphere or Ulbricht sphere measurement. This sensor is able to generate luminous intensity distribution database file (Eulumdat or IES) which simulating a goniophotometer measurement.

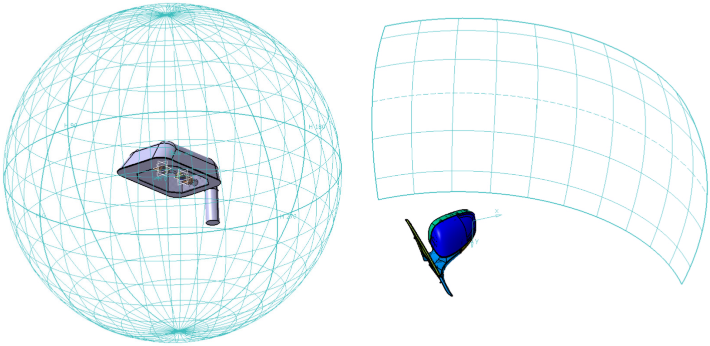

Abb. 8: 3D intensity sensors for different purposes

6. Simulation types

There are two main simulation types available. The first mode is the Interactive simulation, which is a quick, simple, and spectacular way to illustrate the way of the light through an optical system. This simulation cannot use sensors, thus cannot be applied for measurements (Abb. 9).

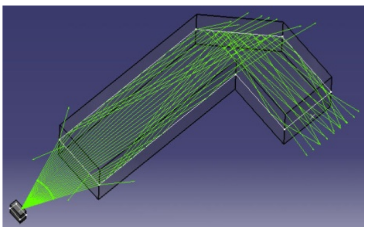

Abb. 9: Result of the indirect simulation

The most important simulation type is the Direct simulation, which can calculate with millions of guided rays using sensors, and requires the accurate setup of light sources and optical properties. This simulation type provides detailed measurement results, but the simulation time is much longer.

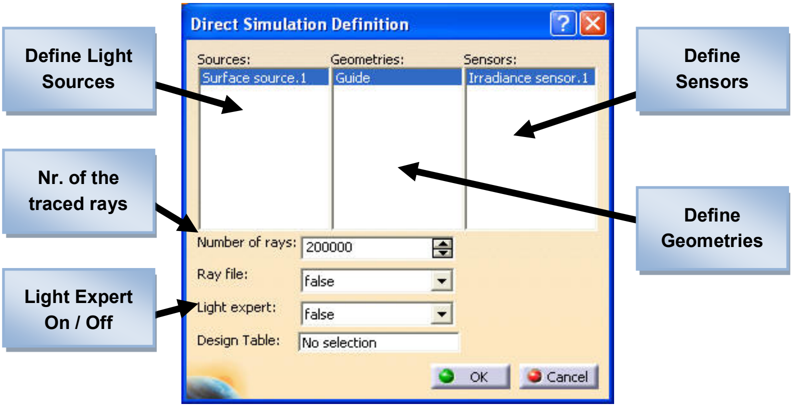

Abb. 10: Direct simulation setup

According to the increase of the number of traced rays, the simulation time also increases (Abb. 11) [3]. We can declare, that with the increase of the ray number, the simulation time grows with direct proportion, and the standard deviation decreases. Thus, to get properly accurate simulation results, the applied ray number should be sufficient, which causes the increase of the simulation time. By Abb. 11, a compromised solution can be declared: complex geometries require at least 3 million, but max. 10 million traced rays.

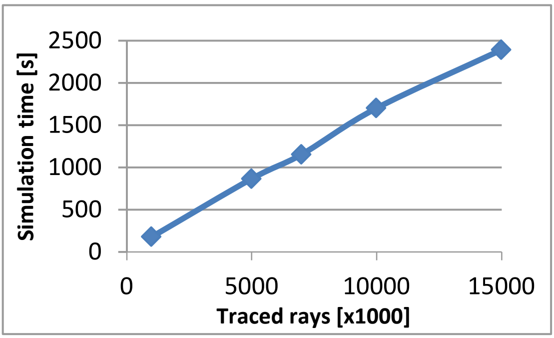

Abb. 11: Correlation between the traced ray number and simulation time

7. Result analysis

The results of the sensors can be displayed and analyzed either in a point or a selected area. The software can calculate the average and the extreme photometrical or radiometrical values, and the uniformity of the analyzed target area. Normalization to a discrete value is also available, thus the conformance of the requirements can be checked easily (Abb. 12.).

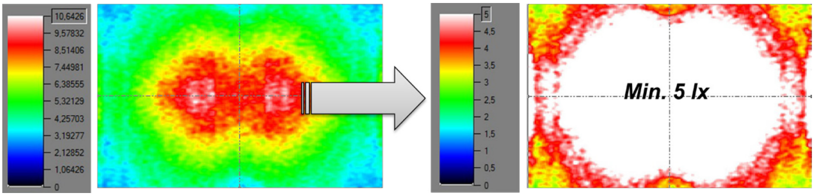

Abb. 12: Normalization of an illuminance result to 5 lx (white area)

8. The "*Light Expert*" application

Light Expert is one of the most useful and brilliant applications of the software. It can reveal ray paths, according to the defined parameters. The application is spectacular, quick, and accurate, and provides great support at the light-analysis and during the product-development. Two different inputs can be defined:

a) sensor area
b) one or multiple surfaces (logic relations are available)

According to the input, the application shows only that ray paths which:

a) get to the selected sensor area
b) contact the selected surfaces

With Light Expert, the influence of discrete surfaces to the light path can be analyzed easily. Thus, the designers can modify the proper geometries, and verify from which directions the light approaches, and which surfaces contribute to the radiation of the discrete sensor surfaces.

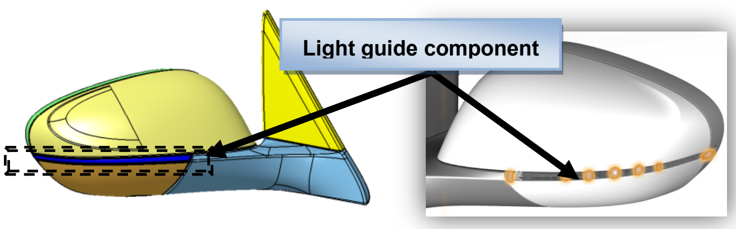

Abb. 13: Car side mirror, with a built-in LED turning signal lamp

Abb.13 illustrates a car side mirror, with a built-in LED turning signal lamp. We had to develop its „Light guide” component. The light intensity distribution of the index lamp can be seen in Abb. 14, left. There is a disproportioned distribution, with a focused light intensity ("hot spot"). In order to eliminate this phenomenon, Light Expert can be used to find the geometries to be modified. After the selection of the target sensor area (Abb. 14, left, illustrated with a dotted square), the paths of light getting to this area have been revealed (Abb. 14, right). This allows us to analyze, which geometries should be modified (Abb. 14, right, illustrated with ellipse).

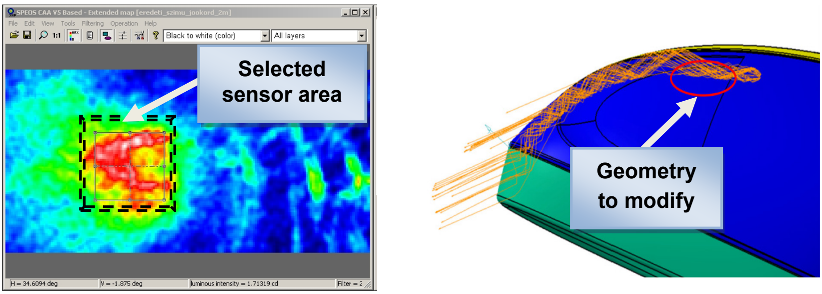

Abb. 14: Light distribution of the turning signal lamp (left), Light Expert analysis of the target sensor area (right)

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