Ray-Tracing Simulation in LCD Development

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Abstract

Recently, at many LCD-related makers, the ray-tracing simulator for lighting analysis is being used to develop light guide plates and optical sheets, which are the parts of a backlight unit. As a result, the effective functions for LCD development, such as a polarization analysis function and a thin film coating function, have been incorporated in the ray-tracing simulator. This paper introduces the example that utilized ray-tracing simulation for lighting analysis in development of backlight units.

Introduction

In recent years, LCDs have been adopted for use as displays in mobile devices such as portable information terminals and mobile phones. To improve the portability of such products, manufacturers are increasingly demanding that displays be lighter in weight and consume less power. Moreover, because these products are frequently used outdoors, screens must deliver higher brightness than would be required for other applications.

In light of such requirements, Sharp is working to make thinner LCD backlight and frontlight units, as well as improve their light utilization efficiency, and has been using ray tracing simulation to advantage in illumination analysis, resulting in more efficient development.

Recently, a variety of vendors have introduced ray-tracing simulators to the marketplace, augmented with new functions oriented toward LCD development. These software packages are contributing to more efficient backlight unit development.

Section 1 below explains the basic functions of ray-tracing simulators used for lighting analysis and includes examples of such analysis as applied to backlight development by Sharp. Section 2 introduces functions recently made available that are particularly effective in LCD development.

1. Basic ray-tracing simulation functions

This section first describes the Fresnel system[1], the basic system underlying geometric optics. This is followed by an explanation of the Monte Carlo method[2], a common numerical analysis method used in ray-tracing simulators. Finally, an analysis model for backlight units is described.

1.1 The Fresnel formulae

When a single ray of light emitted from a light source arrives at an optical element situated in space, a reflected ray and a transmitted ray are generated. The Fresnel formulae can be used to represent their energy.

Consider a ray arriving from a homogenous, isotropic medium having a refractive index n_1 at an angle of incidence θ_i at a medium having a refractive index n_2. The component contained within the plane of incidence of the electric vector of the incident ray is called P-polarized light and the component perpendicular to the plane of incidence is called S-polarized light. In **Fig. 1**, the S-polarized light is oriented in a direction perpendicular to the paper surface.

The respective energy reflectance and transmittance of the P- and S-polarized light can be found from the equations below (here, the optical absorption is ignored).

As : S Component of Incident Ray
Ap : P Component of Incident Ray
Rs : S Component of Reflected Ray
Rp : P Component of Reflected Ray

Medium1 : Refractive index n_1
Medium2 : Refractive index n_2

θ_i : Angle of Incident
θ_r : Angle of Reflection
θ_t : Angle of Transmission

Ts : S Component of Transmitted Ray
Tp : P Component of Transmitted Ray

Fig. 1 Electric field components of polarization vector.

P-polarization energy reflectance

$$\text{rp} = \left| \frac{n_2\cos\theta_i - n_1\cos\theta_t}{n_2\cos\theta_i + n_1\cos\theta_t} \right|^2$$

S-polarization energy reflectance

$$\text{rs} = \left| \frac{n_2\cos\theta_t - n_1\cos\theta_i}{n_2\cos\theta_t + n_1\cos\theta_i} \right|^2$$

P-polarization energy transmittance

$$\text{tp} = \left(\frac{n_2\cos\theta_t}{n_1\cos\theta_i} \right)\left(\frac{2n_1\cos\theta_i}{n_2\cos\theta_i + n_1\cos\theta_t} \right)^2$$

S-polarization energy transmittance

$$\text{ts} = \left(\frac{n_2\cos\theta_t}{n_1\cos\theta_i} \right)\left(\frac{2n_1\cos\theta_i}{n_1\cos\theta_i + n_2\cos\theta_t} \right)^2$$

In the case of normal incidence, the distinction between the P and S components disappears:

$$\text{Energy reflectance} = \left| \frac{n_2 - n_1}{n_2 + n_1} \right|^2$$

$$\text{Energy transmittance} = \frac{4n_1n_2}{(n_1 + n_2)^2}$$

In ray-tracing simulators, every element of the optical model to be analyzed is normally assigned a refractive index as an optical attribute. Then, when the ray arrives at the surface of an element, calculations are carried out using the Fresnel formulae based on its angle of incidence and the refractive indices of the media on both sides of the interface boundary. Normally, calculations are done for the reflectance/transmittance of the P-polarized light and S-polarized light as non-polarized light, and then their average values are used for the reflectance/transmittance at the interface. In other words, the energy of the reflected ray and transmitted ray are taken to be:
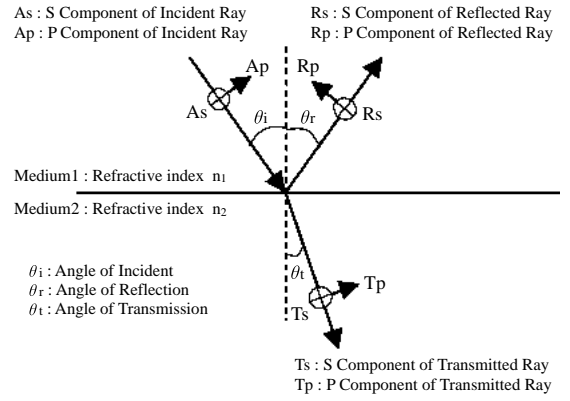
Reflectance = (rp + rs)/2
Transmittance = (tp + ts)/2

1.2 The Monte Carlo method in ray tracing simulation

To analyze illumination systems requires that a large number of rays be generated. Almost all ray-tracing simulators use the Monte Carlo method to generate and manage rays. The Monte Carlo method is an evaluation method that uses the value of a random variable one after another, in order to calculate the solution in question numerically. These variables are used when calculating a solution by transposing the original problem into a certain probable process; for example, performing a mathematical simulation of the physical behavior hidden in the problem.

The Monte Carlo method first considers the emission of rays from multiple points on a surface that has been placed as the light source. The coordinates at which the respective rays arrive on the surface of an object situated in space are obtained by ray tracing calculations. Illuminance distributions, etc., are calculated from the compiled results which take into account the energy that these individual rays have.
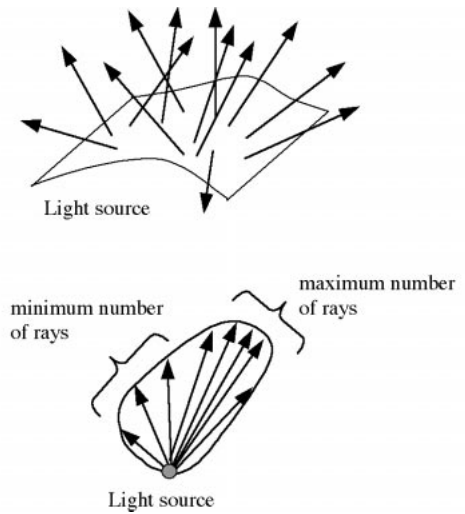

Fig. 2 Ray generation by Monte Carlo Method.

Rays radiate outward from a light source, and so their direction and the coordinates of the point from which they radiate must be determined. The Monte Carlo method uses pseudo-random numbers in determining these numerical values. At this point in time, all rays are regarded as having equivalent energy, and only the direction of radiation of these rays and the density of the generated positions determine the probabilities that characterize the angular distribution characteristics of the light source. Such a determination (**Fig. 2**) means that all light rays represent the same amount of energy, and data processing to tabulate ray-tracing results becomes simple and easy.

Ray-tracing simulators recreate the physical phenomenon of an optical system in which one ray is emitted from a light source, according to the principles of optics. Rays radiated from a light source are split into a reflected ray and a transmitted ray at the boundary surface of objects at which they arrive along their way. How the rays are traced at that point depends on the simulator. For example, it is possible to:

1) Trace all paths of split rays.
In the example in **Fig. 3(1)**, four rays are shown arriving at the boundary. The resulting reflected and transmitted rays (eight total) are then traced.

2) Compare reflectance and transmittance, and trace only the split ray paths that have the most power (dominant energy).
In the example in **Fig. 3(2)**, of the four rays arriving from the light source, only the paths of the transmitted rays (four total), which have the greater energy, are traced.
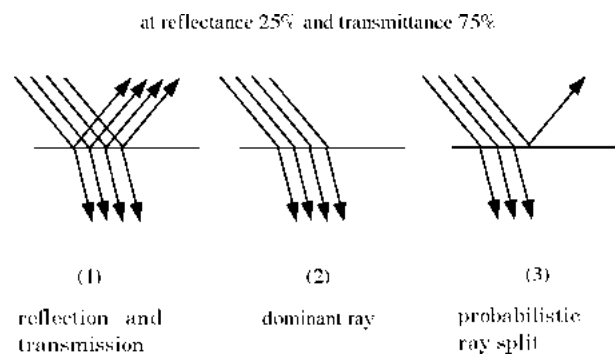

Fig. 3 Ray split on the boundary.

3) Trace only one split ray path, using a probabilistic approach to decide whether to trace the reflected or transmitted ray at each split.

In the example in **Fig. 3(3)**, from the four arriving light rays, three transmitted rays and one reflected ray (four total) are traced.

Because multiple reflections occur in an LCD backlight, computation times tend to be long, and so the method in Example **(3)** is considered most effective. However, for the results of probabilistically determined ray tracing to agree with the physical phenomenon with a high degree of accuracy requires that a large number of rays be traced, and complex analytical models may require several tens of thousands to several million rays.

1.3 An analysis model for a backlight unit

An analytical model for a backlight unit will be explained. The primary optical elements comprising the backlight unit of an LCD are given below (**Fig. 4**).

Fig. 4 Diagram of a backlight unit.

1) Lamp light source
The primary light source used in backlight units are cold-cathode fluorescent tubes. Recently, LED-based light sources have come to be used in mobile devices.
Besides optical attributes as optical elements, light sources such as fluorescent tubes and LEDs need to be given optical attributes such as luminous energy and angular distribution characteristics generated as a light source. The emission spectrum can also be applied as an optical attribute using a simulator capable of handling multiple wavelengths.

2) Light guide plate
A light guide plate is a transparent plastic sheet that converts linear light generated from the light source into a surface source of light incident on the LCD panel. To improve the uniformity of the illumination and boost luminance levels, a prismatic process or dot printing process is applied to the bottom surface.

Refractive index is one optical attribute applied to transparent plastic elements such as light guide plates. Using the Fresnel formulae, the reflectance/transmittance is determined from the angle of incidence at which rays arrive at the element. If desired, optical absorbance within the element can also be taken into consideration by setting a value for optical density. This value allows absorbance of ray energy corresponding to the distance that the ray has penetrated within the medium to be included in calculations.

3) Optical sheet
The optical sheet functions to reflect, diffuse, and/or converge rays radiated from the light guide plate. Various types of optical sheets are available depending on the purpose, such as diffusion sheets that have normal-direction luminous intensity distribution characteristics, prism sheets that improve normal luminance, etc.

When the optical sheet is transparent such as the case of a prism sheet, a refractive index similar to that of light guide plates is applied.
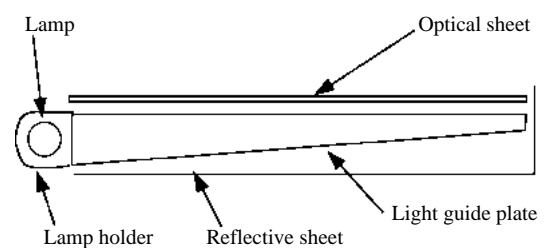
The light scattering properties of elements such as diffusion sheets and diffusion plates are distributed in microstructures within or on the surface of the sheet. Such shapes are difficult to model. In this case, the reflectance and transmittance of that element are determined by measurement, and the obtained diffusion characteristics are set as the optical attributes of the element.

4) Lamp holder and reflective sheet
A reflective sheet covers the lamp or light guide plate. It serves to "re-use" light by reflecting light leaking from the lamp and light guide plate back to the light guide plate.

Both specular-reflection and diffuse-reflection types exist, and for the former, reflectance, and for the latter, diffusion characteristics, are set as optical attributes.

In ray-tracing simulation, a surface must be placed for compiling the results of ray tracing when rays are traced beyond an optical element. In this paper, I call such a surface a "receiver surface." Multiple receiver surfaces can be placed within a single analytical model. The information obtained as computational results includes illumination distribution, luminance distribution, and outgoing radiation angle characteristics. It is important to establish at least one receiver surface conforming to the optical system of the measuring instrument to compare with measurement results. For example, in measuring luminance, the angle at which the ray is received on the receiver surface is determined by the received ray angle of the measuring instrument, and the number of mesh divisions on the receiver surface is determined by the area of the spot diameter of the measuring instrument.

In developing backlight units, luminance distribution and outgoing angle characteristics are checked with particular frequency. The uniformity of the in-plane luminance distribution of the backlight can be investigated based on the results of luminance distribution calculations. And the viewing angle characteristics can be investigated and better normal-oriented luminance provided based on the results of outgoing angle characteristic calculations.

1.4 Prism sheet analysis example

An example of an analysis of a prism sheet used in compact LCD worked out at Sharp is presented here. The prism sheet is an optical sheet arranged on top of the light guide plate, and functions to concentrate the ray emitted from the light guide plate in the normal direction, thereby improving brightness as observed directly from the front.

In the analysis model, two prism sheets were arranged one on top of the other, aligned so that the prism directions were orthogonal. The apex angles of the top and bottom prism sheets were used as parameters, and the combination of apex angles that resulted in higher normal luminance (**Fig. 5**) were investigated.
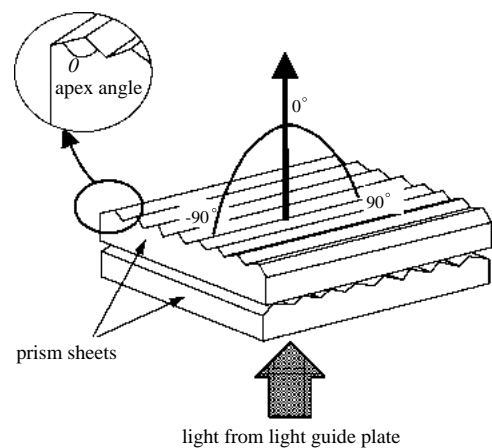

Fig. 5 Diagram of prism sheets.

In this case, the attributes of the lamp and light guide plate were fixed. To investigate optimal prism sheet characteristics for that optical system, the angular characteristics of the ray radiated from the light guide

plate were measured, and those characteristics were set as a surface light source. The receiver surface was set to observe the radiated angle characteristics, and the angle to be observed was set in 5-degree increments. Using 500,000 rays, the calculation time was just over five hours with an error of 10%.

Fig. 6 is a graph illustrating the results of that analysis. The horizontal axis of the graph is the grazing angle of rays radiating to the prism surface. A difference in peak intensity of 130% appeared, depending on the combination of apex angles of the prisms. Differences in angular characteristics can also be investigated. This kind of simulation allows designers to set parameters freely and check a wide range of combinations to determine best to worst situations.
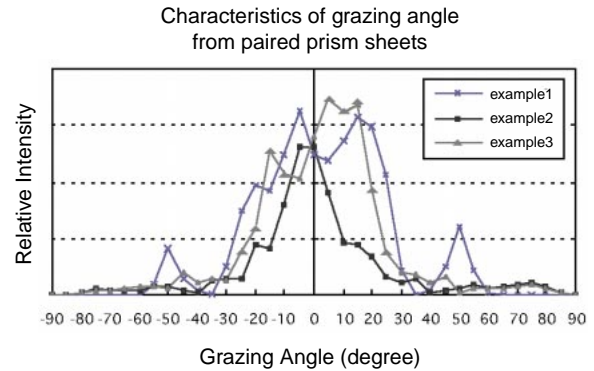

Fig. 6 Result of ray-tracing simulation.

The present example uses only combinations of prism apex angles as parameters, but there are several other parameters that should be taken into consideration such as prism pitch, prism depth, prism material, etc. Doing hypothetical experiments using ray-tracing simulation on combinations of these parameters prior to prototyping to determine optimum combinations of conditions makes it possible to reduce prototyping costs and shorten development times.

2. LCD functions

This section presents several important functions that can be used effectively in the development of LCDs.

2.1 Texture mapping function[3][4]

The light guide plate in a backlight unit converts a linear light source such as a fluorescent tube into a surface light source to illuminate an entire LCD panel. Naturally, it is desirable that the brightness be uniform over the entire surface. One way to accomplish this is to screen print a pattern of white dots on the bottom surface of the light guide plate. A ray striking these dots is diffusely reflected. To attain uniform brightness over the entire area, the size and density of the dots are varied according to where they are located within the light guide plate. In general, the dots are smaller and sparsely printed in the vicinity of the light source. As the distance from the light source increases, the size of the dots becomes larger and they are printed with greater density.

Setting parameters for these dot patterns is simple and easy, thanks to supplemental texture mapping functions provided to facilitate such calculations. These functions create distributions for dot printing patterns using image data such as bit-mapped patterns, and operations are available to simulate affixing them to the bottom surface of the light guide plate. The optical attributes of the light guide plate and the optical attributes of the dot parts can be individually specified, making ray tracing possible for the dot-printed type of light guide plates.

Analyzing dot-printed light guide plates using only conventional functions required that the dot areas be created as individual surfaces separate from the bottom surface of the light guide plate. The operations to create such a model were complicated and cumbersome, plus the number of surfaces became huge,

significantly slowing the computational response of the simulator and dramatically increasing the time required for analysis.

2.2 Polarization function[5)6)]

LCDs are display devices that make use of the polarization of light. Ordinary LCD panels are equipped with a sheet polarizer, and it converts light coming from the backlight unit to linearly polarized light incident on the LCD panel. The amount of light from the backlight unit is reduced by nearly half as it passes through the sheet polarizer. To analyze such an element requires that parameters be set for a linear polarizer. In addition, to increase the light utilization efficiency, an optical sheet is available to make it possible to split the polarization components, with one component transmitted, and the other component re-used by being reflected back to the backlight unit side (**Fig. 7**). Analyzing such an optical sheet requires that each polarization component be traced separately.
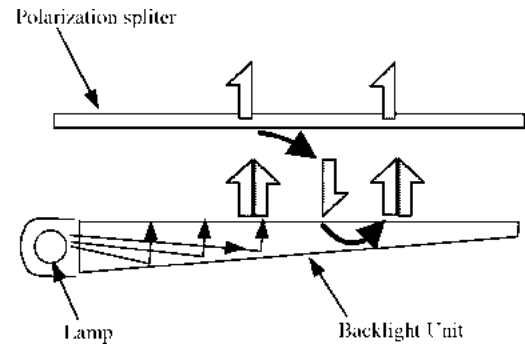

Fig. 7 Diagram of polarization splitter.

Polarization settings for the ray-tracing simulator include:
(1) Setting the polarization configuration for the rays, and
(2) Setting a parameter to indicate that the polarizer faced toward the surface of the element.

Making these settings enable the polarization configuration and energy of the rays after passing through the polarizer to be investigated.

2.3 Thin-film coating function[7)]

Thin optical coatings, such as anti-reflection films, consisting of a dielectric or metallic material, may also be applied to a portion of the surface of elements in the backlight unit. A "thin-film coating function" makes it possible to set the spectral characteristics of these multi-layer films as an optical attribute.

Using the thin-film coating function, the energy reflectance/transmittance for P- and S-polarized light are determined in advance for each wavelength and each angle of incidence between specified media based on measured values and/or the Fresnel formulae. Their values can then be set as optical attributes of a surface.

In a model such as the polarization splitter shown in **Fig. 7**, the reflectance and transmittance of P- and S-polarized light for the coating surface are applied as optical attributes of the surface. Combining this function with the polarization function introduced previously enables ray tracing of individual P- and S-polarized light rays.

Conclusions

This paper introduced a number of functions provided in ray-tracing simulators applicable to the design of LCDs. In addition to a suite of conventional basic functions, supplemental polarization functions allow

analysis of a wide variety of optical elements, making these simulation packages an effective means of backlight unit design.

However, recently, new elements have appeared in backlight unit design in which a microscopic process with a feature size of only several microns is applied to the light guide plate and/or optical sheet. To analyze such an element requires understanding the phenomenon in which light is considered to be a wave, in other words, taking into account interference and the diffraction of light. The Maxwell equations for the simulation of wave optics can be solved using FTTD and finite limit methods, but the range of analysis is small, on the order of several microns to several tens of microns. Analyzing a model of greater than several mm such as a backlight is impossible as things stand now. In the future, we can anticipate the debut of simulators in which ray tracing simulation and wave optics are merged.

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