IMPROVEMENT OF ACCURACY IN LIGHTING SIMULATION BY FLUX TRANSFER METHOD

Mitsugu HIRATA, Hideki GAMA and Hajimu NAKAMURA

Engineering Planning Department
Matsushita Electric Works, Ltd.

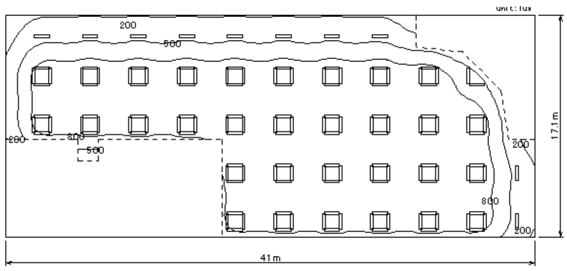
1048, Kadoma, Osaka 571-8686, Japan

ABSTRACT

In this paper, we describe the characteristics of "Luminous Planner" as a general-purpose lighting design tool, and of "LSR(Lighting Simulation Radiosity)", which is capable of high-precision lighting simulation by taking space reflection into consideration. The "LSR" divides architectural shapes into small polygons and pursues flux transfer in each small polygon. We applied the progressive refinement approach to the "LSR", required calculation time and memory have been reduced. Further improvement of the calculation method has also enabled handling of intensity distribution of luminaire and transmittance of surface. And calculation accuracy has been enhanced through the use of perspective drawings and scan lines in form factor calculation. Experiment results to confirm the accuracy of calculations are presented in comparison of calculation and measure.

INTRODUCTION

Appropriate lighting design is essential for comfortable, efficient, economical and attractive architectural spaces. Lighting design involves the selection of light sources, the selection and arrangement of lighting apparatuses, and lighting simulation comprised of illuminance and luminance calculations. Lighting simulation has been performed with the use of computers for a long time, since complex calculations must be carried out with large quantities of optical data concerning luminaire. In recent years, in particular, technical developments such as computation speed increase, memory size expansion, image display improvement and advanced communication technology have made it possible to perform complex simulations on low-priced hardware. In 1971, our company developed software for main frame computers that enables a plotter to produce isolux drawings, as shown in Fig. 1. This software has since undergone some improvements, including functional reinforcement and platform change. At present, it is marketed as personal computer software under the name "Luminous Planner" for lighting designers in Japan.



	(luminaire)
Model No.	F425HEX
Model Name	FL40 X 2
Lamp	FHF32EX-N(4500)
Total Luminous Flux	9000 lumen
Maintenance Factor	0.66
Light Distribution Code	K36624
Mounting Height	3 m
Q'ty of Luminaire	136 sets

	- - - - - - - - -
Average Illuminance	782 lux
Minimum Illuminance	69 lux
Maximum Illuminance	1049 lux
E min./E ave.	0.088
E min./E max.	0.066

Fig.1 Example of isolux drawing

The application of three-dimensional computer graphics to lighting simulation began in 1987. In the beginning, the objective was only to examine direct illuminance from luminaire using ray-tracing software. Later, we developed "LSR" (1991), simulation software based on the radiosity method, which takes space reflection into consideration, and introduced software based on the bi-directional ray tracing method. In this paper, we describe the characteristics of "Luminous Planner" as a general-purpose lighting design tool, and of "LSR", which is capable of high-precision lighting simulation.

GENERAL-PURPOSE TOOL

Fig. 2 shows example screen displays of "Luminous Planner". This software performs interreflection and illuminance distribution calculations, and produces isolux drawings based on input data such as room form, luminaire arrangement and installation angles; it has the following characteristics:

(1)Any luminaire arrangement and installation angles can be set.

(2)Average illuminance in any given polygon can be calculated.

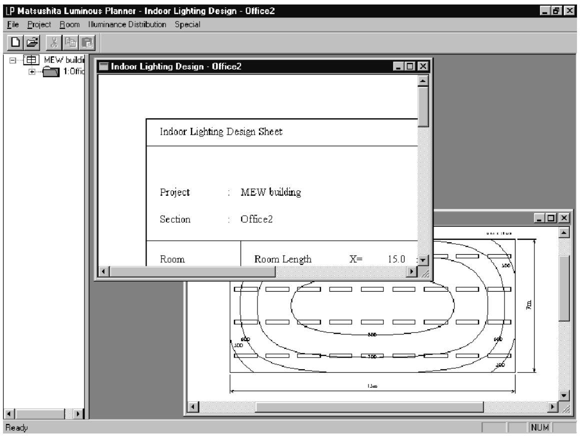


Fig. 2 Example screen of "Luminous Planner"

(3) Interreflection element calculation is performed by the flux transfer method, on the assumption that the ceiling, walls and floor are completely diffused reflection surfaces; calculation errors are more likely to occur when marked luminance change is found among ceiling, walls and floor, due to indirect lighting and other reasons, and when interreflection elements are large.

However, this software can be used for most illumination distribution evaluation tests, since indoor lighting is direct in most cases, so there is not much illuminance increase resulting from interreflection.

(4) Using a digitizer, it is possible to input data such as luminaire arrangement and room forms from architectural drawings.

(5) Overall indoor lighting design function

This is the function of calculating the required number of units of luminaire, determining luminaire arrangement and outputting calculation results by the flux method, based on input data concerning room forms and required illuminance, and selecting luminaire to be used; to calculate lighting rates, the ZCM method is used.

(6) Emergency lighting fixture arrangement design function

Concerning lighting provided by an auxiliary power supply installed in anticipation of power failure during fires and other accidents, it is necessary, according to the Japanese standards, to secure 1 lux (2 lux for fluorescent lamps) or more at the point where floor surface illuminance is lowest. To fulfill this condition within economic restrictions, it is necessary to optimally arrange appropriate luminaires. "Luminous Planner" is capable of automatically determining arrangements that satisfy this condition.

COMPLEX INTERREFLECTION CALCULATION TOOL

The "LSR" divides architectural forms into small polygons and pursues and calculates flux transfer in each small polygon, to calculate the illuminance distribution of indirect lighting, whose calculation errors tend to be large with simple interreflection, and to calculate illuminance distribution while taking shading by architectural forms into consideration.

FLUX TRANSFER METHOD

Luminance of a section of a space can be obtained based on direct light from the source and interreflection from other objects. In the field of lighting engineering, numerous attempts have been made since many years ago, to calculation interreflection. Methods developed thus far include the method using integral equations and the Monte Carlo method. One such method, the flux transfer method, is most widely employed. Its principle is briefly explained below. Incidentally, "LSR" handles only uniformly diffused reflective light and transmitted light.

For example, in a rectangular parallelepiped room, when the ceiling is referred to as 1, the four walls as 2 and the floor as 3, the brightness of the walls, since it is equal to the sum of direct light from the source and light reflecting from all surfaces, can be expressed by the formula below:

$$M_2 = M_{02} + \rho_2 (F_{12} M_1 + F_{22} M_2 + F_{32} M_3)$$

(This formula represents a state in which reflection is repeated many times until saturation.)

where,

M_1, M_2, M_3 = luminous exitance of the ceiling, walls and floor; equivalent of radiosity(lm/m^2)

M_{02}: luminous exitance of the walls by direct light from the source(lm/m^2)

ρ_2: Reflectance of the walls; percentage of fluxes directed to the walls and reflected by them

F_{12}: Percentage of light from the ceiling directed to the walls; this is called the form factor, since it depends solely on the forms of the ceiling and walls, and their relative position.

F_{22}: Wall-to-wall form factor

F_{32}: Floor-to-wall form factor

As for similar formulas concerning ceiling and floor, 3-row, 3-column simultaneous linear equations can be formulated. In general, when a space is divided into a given number of parts ("n"), n-row, n-column simultaneous linear equations can be formulated as shown below.

$$M_i = M_{0i} + \rho_i \sum_{j=1}^{n} F_{ij} M_j$$

Form factor can be calculated using the following formula (see Fig. 3):

$$F_{ij} = \frac{1}{\pi A_i} \int_{Ai} \int_{Aj} \frac{\cos \theta_i \cos \theta_j}{r_{ij}^2} \, dA_i \, dA_j$$

where,

F_{ij} : Form factor (element-i -to- element-j)

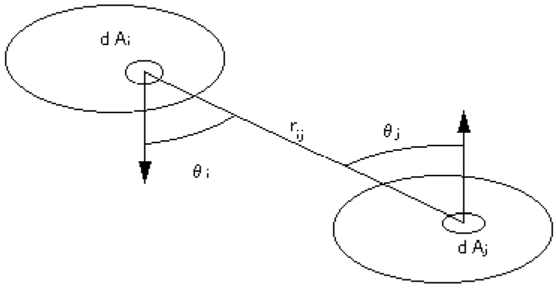


Fig. 3 Form factor

The flux radiation of each surface in consideration of interreflection can be calculated with the following formulas. Interreflection calculation by "Luminous Planner" is performed analytically by dividing a cubic room into three parts (n=3), i.e. ceiling, walls and floor.

However, an analytical approach is not appropriate for calculating interreflection, in consideration of the shades of objects in the space, such as a desk, or in consideration of brightness imposed by a spotlight and so forth. This is because such calculations require dividing the space into very small parts (several tens of thousands), thus very highly elevating the "n" number and producing a large number of form factors (n squared), necessitating a long time for form factor calculation and an enormous storage capacity.

In 1988, M.F. Cohen *et al.* announced a method for solving this problem of required calculation cost and storage capacity; that is, the Progressive Refinement Approach. By applying this Approach to the system discussed here, required calculation time and storage capacity have been reduced; further improvement of the calculation method has also enabled handling of transmission in the same manner as the light distribution and reflection of arbitrary luminaires. Calculation accuracy has been enhanced through the use of perspective drawings and scan lines in form factor calculation.

ALGORITHM

First, surfaces comprising a space are divided into small elements; the total number of these elements is referred to as "n".

Secondly, the initial flux radiation of each element by direct light is calculated by point-by-point method, and the reflected flux of each element is obtained by the formula below:

$$B_k = A_k M_{0k}$$

where,

B_k: Flux radiation of element-k (lm)

A_k: Area of element-k (m²)

M_{0k}: Initial luminous exitance of element-k (lm/m²)

Next, the element with the largest B_k among all the elements is identified; this element is referred to as "i"; flux transfer of the remaining elements of the flex reflected from "i" is calculated using the following formulas:

$$M_j = M_j + (\rho_j F_{ij} + \tau_j R_{ij}) B_i / A_j$$

$$B_j = B_j + (\rho_j F_{ij} + \tau_j R_{ij}) B_i$$

$$(j=1,2,...,n)$$

where,

M_j : Luminous exitance of element-j

(initial setting is M_{0j})

ρ_j : Reflectance of element-j

τ_j : Transmittance of element-j

F_{ij} : Form factor (element-i -to- element-j front)

R_{ij} : Form factor (element-i -to- element-j reverse)

After this calculation, B_i is reset to zero. Then, the total sum of B_k of all elements is calculated. This value corresponds to the total of fluxes not yet radiated to the space, and if this is sufficiently small, calculation may be completed. At the same time, the solution to M_k is also obtained.

If convergence has not been achieved, the same procedure is repeated, starting with patches whose B_k value is much larger.

The characteristics of "LSR" include the following:

(1)Architectural form definition and patch division

Three-dimensional forms are defined in three-dimensional polyhedrons using CAD software. Elements are defined by dividing surfaces constituting polyhedrons into grids at prescribed intervals. Elements serve as units of radiation and light reception in interreflection and transmission calculations.

(2)Calculation of direct flux radiation by luminaires

As luminaire data, light distribution, installation positions and angles are input. Light distribution refers to the intensity of light emitted from luminaires measured in different directions, and can be indicated by curves such as Fig. 6. The installation positions of luminaires are expressed on three-dimensional coordinates, and installation angles refer to displacement angles from the standard position given in rotational angles on x, y and z axes. Based on these data and by the inverse square law, the direct flux radiation of each element is calculated. In the case of a surface light source (e.g. a fluorescent lamp), the light source is divided for calculation, since the size of the light source must be taken into consideration.

(3)Form factor calculation

In Cohen's method, form factors between elements are obtained using the semi-cube unit sphere method. Our system originally used software of the scan line Z buffer method for perspective conversion as well. Since high-speed perspective conversion by graphic hardware cannot be performed, the single-plain (screen) unit sphere method, as shown in Fig. 4, has been adopted so that only one session of perspective conversion is required.

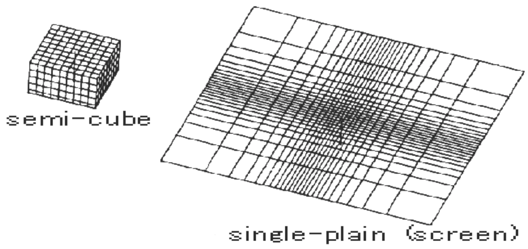


Fig. 4 Form factor calculation

With this method, as compared to the semi-cube unit sphere method, the plain in single-plain perspective drawings must be fully enlarged to capture light emitted from patches. For accurate form factor calculation, however, it is necessary to minimize screen resolution, while a larger screen requires a longer time for calculation. Therefore, pixel size was differentiated according to screen position, as illustrated, so that the apparent size of pixels viewed from emitting patches would be the same. In this way, calculation accuracy and sufficient screen size have been achieved at the same time.

(4)Rendering

Images are calculated either by the scan line Z buffer or ray tracing method.

MEASUREMENT

To confirm the accuracy of calculation by "LSR", indirect-lighting model illuminance was measured, and the results were compared to calculated values. The model used in this experiment is shown in Fig. 5. measured and calculation conditions below:

Reflectance(measured): inclined ceiling 83%, horizontal ceiling 81%, walls 81%, floor 18%

Luminaire: wall luminaire

Lamp: 40-watt fluorescent lamp (flux: 3560 lumen)

Light distribution: see Fig. 6

Fig.7 is results of measured illuminance distribution. And fig.8 is results of calculation under the same conditions. Fig.9 is a picture of rendering image made by using the calculation results above. Measure and calculation results, are compared in the Fig.10.

We make an analysis of difference between measurement and calculation results, as followings. Fig.10 indicates almost all measurement values are a little more than the calculation ones. We guess it is the first reason of the difference between measurement and calculation that total luminous flux of lamp for measurement is a little more than that for calculation. We, to calculate the illuminance on the wall and floor, used a total luminous flux after the lamp has been operated for a hundred hours. And we, to measure, used a new lamp before operating for a hundred hours.

Furthermore we guess illuminance calculated by reflected light on the surface of ceiling, wall and floor makes a little difference with measurement, because a type of refection, matte surface, in calculation is a little different with actual one.

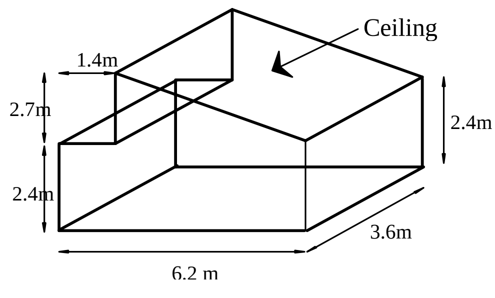


Fig. 5 Room for measurement

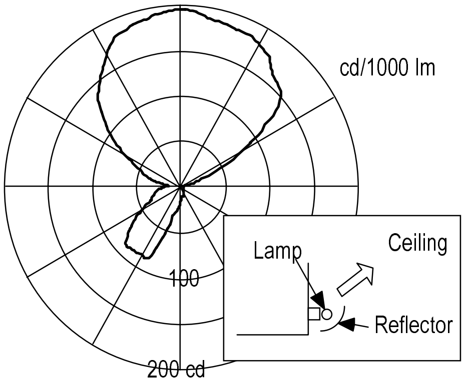


Fig. 6 Luminaire for measurement

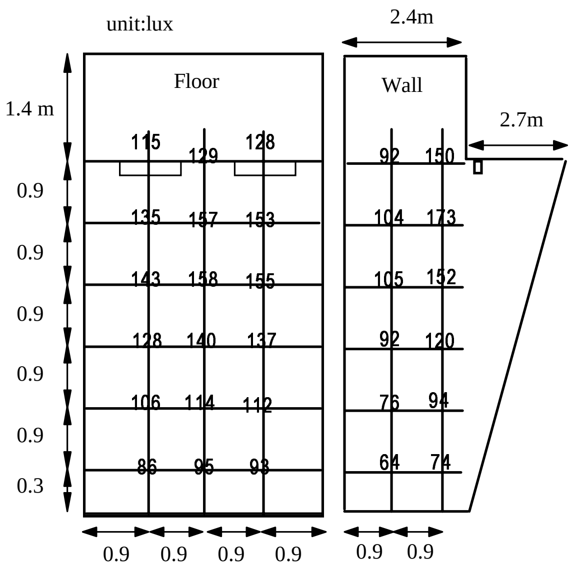


Fig. 7 Measured illuminance

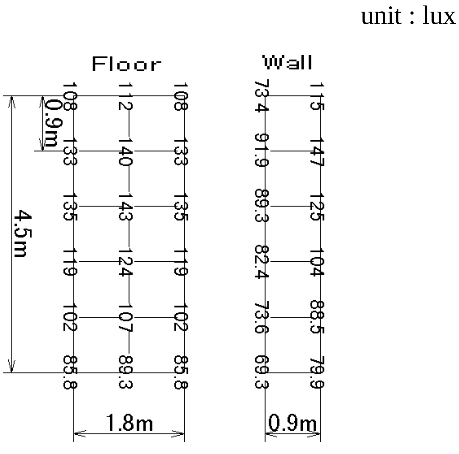


Fig. 8 Calculated illuminance

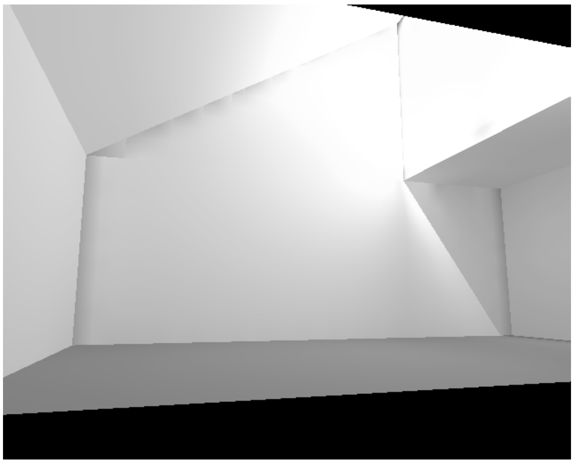


Fig. 9 Rendering image

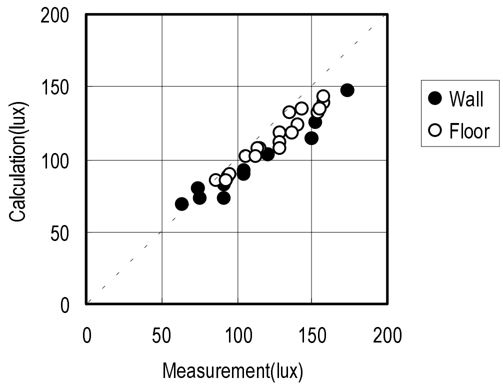


Fig. 10 Comparison of calculation and measurement

CONCLUSIONS

In Cohen's method used in "LSR", interreflection equations are solved by the Gauss-Seidel method. Physically, it is the same as pursuing fluxes in the direction of light from the source. This method is better than the analytical solution of interreflection equations, for the following reasons:

(1)Calculation is speedy, since light-pursing elements with large un-radiated fluxes are selected.

(2)The use of graphic hardware for perspective conversion accelerates calculation, since the unit-sphere method employing the perspective drawing method is used for form factor calculation (graphic hardware is not used in our system).

(3)Form factor storage capacity can be extensively reduced from n squared to n, since form factors are calculated for all elements from elements that radiate fluxes, when necessary.

(4)Approximate solutions can be calculated rapidly, calculation accuracy increasing as calculation progresses; calculation time can be reduced, since calculation can be terminated once required accuracy is obtained. In addition to the advantage of the radiosity method, the following improvements have been added to “LSR”:

(a)The light distribution characteristic of lighting fixtures can be examined.

(b)Transmitted light can be taken into consideration.

(c)Calculation accuracy has been improved by employing the single-plain unit sphere method for form factor calculation.

We think the single-plain unit sphere method in “LSR” is actually useful method for a lighting simulation to make a good lighting plan for comfortable or pleasant environment.

ACKNOWLEDGEMENTS

We wish to thank people concerned for their valuable assistance and cooperation to complete this technical paper.

REFERENCES

(1)M.F.Cohen, S.E.Chen, J.R.Wallance, D.P.Greenberg “A Progressive Refinement Approach to Fast Radiosity Image Generation”, SIGGRAPH ’88.

(2)M.Hirata “Lighting simulation by radiocity method”, PXEL No.110 (1991)