Illuminance Distribution Uniformity in a Room : Computer Simulation Used Kinoform

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ABSTRACT

The purpose of this paper is to study a uniform illuminance distribution on a floor surface in a room, controlling the daylight incidented from a window with a kinoform. In this paper, the illuminance distribution is computed using finite element procedure. The daylight is irradiated the parallel wall with the window by the kinoform, next, the reflection from the wall surface to the floor surface is computed. The result shows that the illuminance distribution on the floor is improved very much compared with the case that the kinoform is not installed on the window.

1. Introduction

The daylight incidented from windows forms an illuminance distribution in a room, but its illuminance distribution on the floor surface is not uniform. So, we try to make the illuminance distribution on the floor surface uniform with a kinoform[1] by computer simulation using finite element procedure[2)3)].

In this paper, we compute a illuminance distribution on the assumption that a kinoform is installed on a window faced to due south. First, we make the daylight incidented obliquely from the window horizontally in order to irradiate only the parallel wall with the window. Then the incident angles of the daylight change variously throughout a year or a day. We consider the change of the phase difference originated from this change of the incident angle on the kinoform surface, and synthesize kinoforms for each incident angle. In this computer simulation, we do not use the wavelength of the daylight, but one of laser light ($6.328\times10^{2}nm$) because of the characteristics of the kinoform.

Next, the illuminance distribution which is formed by the reflected light from the wall surface is computed. We consider to the 3rd reflection, as the light incidents from the window propagates to the wall, and reflects to the ceiling, next to the wall, last to the floor. A illuminance distribution which unify the illuminance distribution on the floor surface is formed on the wall surface. In practical computations, interreflection equation is solved on condition that the illuminance distribution on the floor surface is uniform, and the initial illuminance on the wall surface is determined. Last, the kinoforms whose reconstructed images are this initial illuminance are synthesized for each incident angle.

When one of these kinoforms which is suited for incident angle is installed on the window, the illuminance distribution on the floor surface keeps the uniform distribution, even if the light incidents at any angles.

2. Principle of kinoform and application to illuminance

Kinoform is one of the computer generated holograms(CGH). Its characteristics are that the amplitude of the incident light on the kinoform is regarded as constant, and only the phase term is recorded on a photo sensitive material as thickness. It can be synthesized only computer because the phase term has to be recorded, but it has the advantage that we can get the image of the virtual object. The incidented light is bent by the diffraction effect of the kinoform. The diffraction efficiency of kinoform is higher(ideal value : 100%) than other holograms. For the reasons mentioned above, we consider kinoforms are appropriate for illumination.

First, the case the light incidents normally to the kinoform is considered. The data of the distribution we want to obtain from the kinoform is synthesized. This distribution is expressed input distribution. The input distribution is Fourier transformed in order to get the distribution on the kinoform surface, and only the phase term is expressed by gray scale to synthesize CGH (Figure 1). This CGH is recorded on the photo sensitive material. The photo sensitive material is bleached to remove the silver particles. This bleached CGH is kinoform. So the kinoform have the uneven structure shown in Figure 2(a). The thickness of d_{Max} retard the phase by 2π rad. It is exposed to the light normally, and the input distribution is reconstructed. In this paper, the input distribution is the initial illuminance distribution on the wall surface.

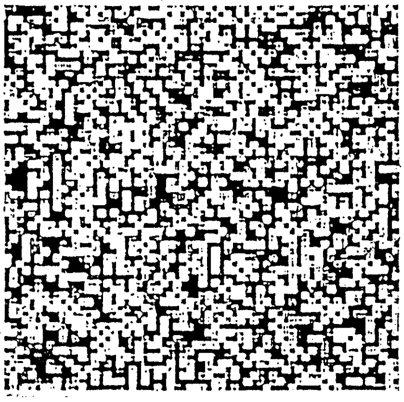

Fig. 1 Computer generated hologram

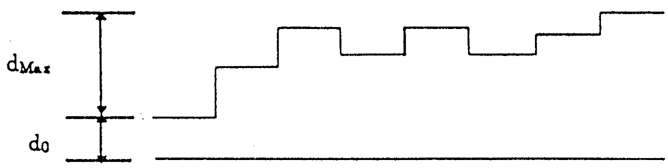

Fig. 2(a) Cross section of kinoform

Secondly, the case the light incidents obliquely to the kinoform is considered. The daylight incidents at various angles on the window installed the kinoform. So, the phase difference is formed on the kinoform. The phase difference is retouched by the kinoform so that the incident light is made horizontally and that it is illuminated only the parallel wall with the window. This concept is shown in Figure 2(b).

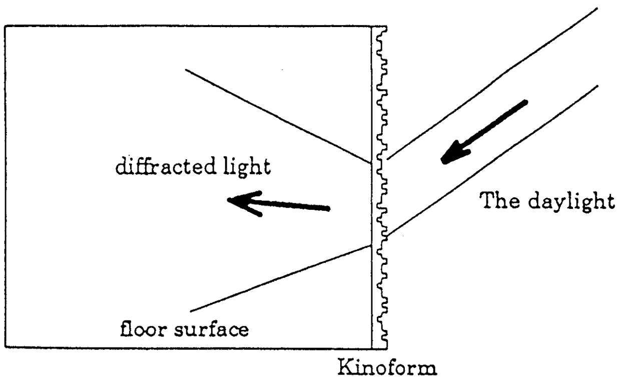

Fig. 2(b) Conception of the propagation of the incident light

The ratio of the kinoform ti the room is drawn larger than the real ratio in this figure. The incident angles of the daylight change variously throughout a year or a day. In this paper, the typical angles are chosen, and kinoforms are synthesized for each angle. The kinoform can change the direction of the light like a prism, and the angle is been free to decide because the kinoform is synthesized by a computer. When the kinoform is installed on the window, we can propagate the light at any direction in the room.

These two kinoforms --- kinoform to synthesize the initial illuminance on the wall surface and kinoform to retouch the phase difference of the light incidents obliquely --- are combined to one kinoform. This kinoform is installed on the window, and the floor surface is illuminated uniform even if the light incidents at any angles.

3. Interreflection equation considered reflection orders

Interreflection equation

$$E_i = E_{0i} + \sum_{j=1}^{m} \rho_j F_{ij} E_j \qquad (1)$$

E_i : final illuminance of element i

E_{0i} : initial illuminance of element i

ρ_j : the reflectance of element j

F_{ij} : form factor from element i to element j

E_j : final illuminance of element j

This equation is extended to one considered reflection orders.

The final illuminance of element i after (n)th reflection denoted by $E_i^{\,n}$ is equal to the sum of the final illuminance of element i after ($n-1$)th reflection denoted by $E_i^{\,n-1}$ and the increase of the indirect illuminance from other elements by interreflection. The increase of the indirect illuminance is produced by the final illuminance of each element after ($n-1$)th reflection.

$$E_i^{\,n} = E_i^{\,n-1} + \sum_{j=1}^{m} \rho_j F_{ij} E_j^{\,n-1} \qquad (2)$$

Next equation is expressed by the initial illuminance $E_j^{\,0}$.

$$\begin{pmatrix} E_1^{\,n} \\ E_2^{\,n} \\ \vdots \\ E_m^{\,n} \end{pmatrix} = \begin{pmatrix} 1+\rho_1 F_{11} & \rho_2 F_{12} & \cdots & \rho_m F_{1m} \\ \rho_1 F_{21} & 1+\rho_2 F_{22} & \cdots & \rho_m F_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \rho_1 F_{m1} & \rho_2 F_{m2} & \cdots & 1+\rho_m F_{mm} \end{pmatrix}^{n} \begin{pmatrix} E_1^{\,0} \\ E_2^{\,0} \\ \vdots \\ E_m^{\,0} \end{pmatrix} \qquad (3)$$

The illuminance distribution is computed with this matrix.

4. Simulation

The flow chart of the simulation in this paper is shown in Figure 3. In this paper, we consider a cubic room shown in Figure 4 as a illuminance field. The size of the room on simulation is 16×16×16. The size of the window is 16×16, too, and it is on surface 3. Each surface is divided in 8×8 elements. The size of the room and the division number are decided by power of the using computer. A kinoform is installed on surface 3 (window). Only surface 2 (wall surface) is irradiated by the reconstructed image obtained from the kinoform. And the case that surface 1 (floor surface) is made uniform by the reflected light from surface 2 is computed. Each surface's reflectances are 0.2/0.8/0.5 on the surface 1, surface 3, and the other surfaces, respectively[4].

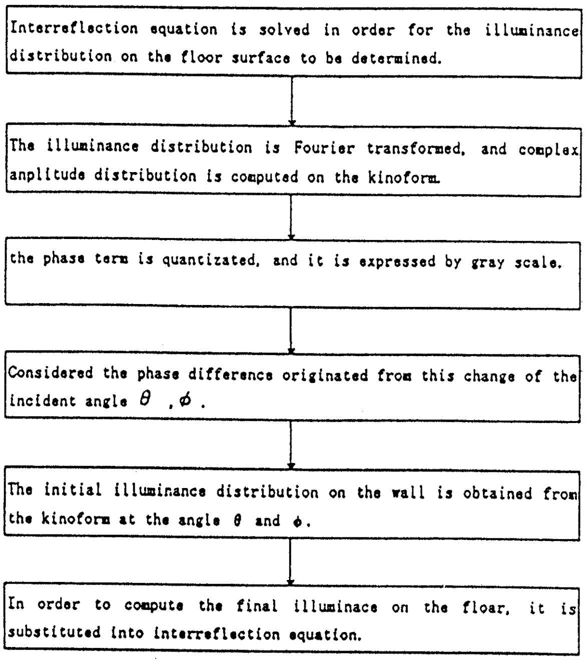

Fig. 3 Flow chart of the simulation

There are two methods, unit-sphere method and boundary integral method, to compute the form factors. In this paper, we use both two methods. Each expression has integrals, so each element which is divided into finite elements is subdivided into 10 subelements to compute in a computer.

First, the initial illuminance on the wall surface is given by solving equ.3 on condition that the final illuminance on the floor surface is uniform. Though equ.3 is solved by using Crout method in this computer simulation, the initial illuminance on the wall surface include the minus initial illuminance. Then we try following two methods for removing the minus illuminance.

Method 1 : All minus illuminance is regarded as 0
Method 2 : The smallest illuminance is standardized (0)

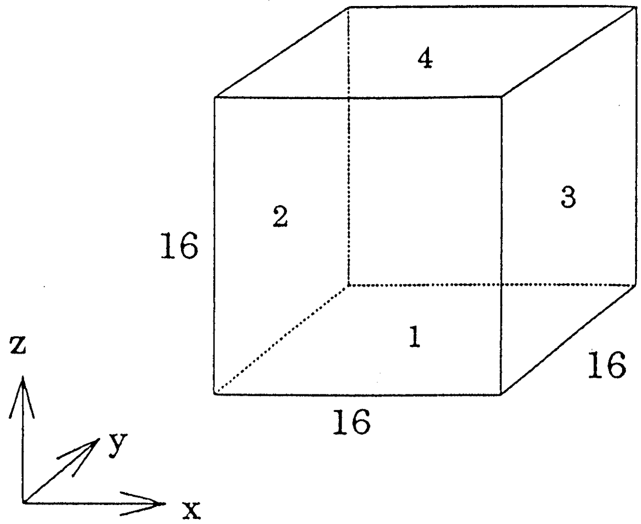

Fig. 4 Structure of the room and position of each face

Mentioning about Method 1, the nearest illuminance to the minus illuminance is 0 in the illuminance exists actually, so the minus illuminance is replaced with 0 approximately. About Method 2, the difference between the illuminance of each element is kept, and the smallest illuminance is standardized (0) .

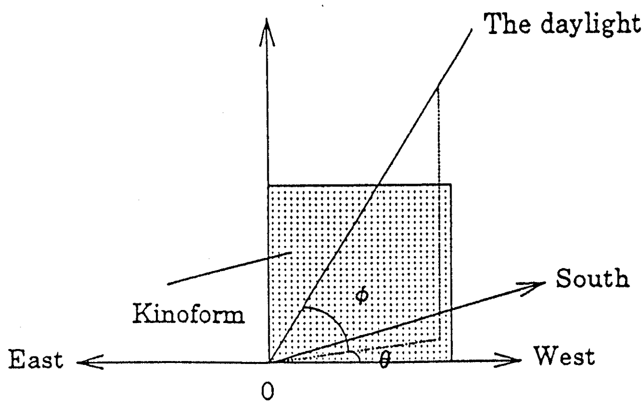

Fig. 5 The relation between the direction and θ, ϕ

Next, this initial illuminance distribution is formed by the kinoform. The daylight incidents at various angles on the surface 3. Therefore, the kinoforms are made for each of these angles in the same method. The incident angles of the daylight are determined by referencing the movement of the sun on vernal equinox day and autumnal equinox day, the summer solstice, and the winter solstice. And the computation about $\theta > 90°$ is omitted because the results are expected symmetrical with respect to 90° . The relation between the direction and θ, ϕ is shown in Figure 5. The incident angles θ , ϕ are shown in Table 1. These values are decided on the basis of the values in Tokyo[5].

Table 1 Angles of the incident daylight

vernal equinox day autumnal equinox day		the summer solstice		the winter solstice	
θ	ϕ	θ	ϕ	θ	ϕ
30	19	30	42	30	0
45	28	45	51	45	8
60	37	60	60	60	16
75	46	75	69	75	24
90	55	90	78	90	32

by degree

Last, the reflected light of the reconstructed image obtained from the kinoform, and next, the final illuminance on the floor surface is computed.

In our computer simulation, we use iterative Fourier transform algorithm to diminish the noise of the reconstructed image obtained from the kinoform[3]. Iterating number is 20, step number is 20, and quantization level is 8.

5. Results

The results of simulation are shown as follows. Figure 6 is the value of the gray scale. Figure 7 and 8 are the initial illuminance on the wall surface. Figure 7 is the result that form factors are computed by unit-sphere method, and (a) is the result that the minus illuminance is dealt with Method 1 and (b) is with Method 2. Figure 8 is the result that form factors are computed by boundary integral method, and (a),(b) are the results that the minus illuminance is dealt with Method 1, Method 2, respectively. The scales of the gray scale in Figure 7 and 8 are shown in Figure 6. The value of this gray scale is relative value.

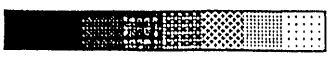

Fig. 6 Relative value of gray scale

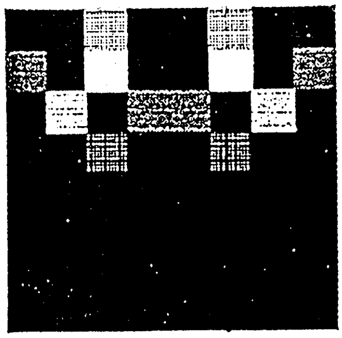

Fig. 7(a) Initial illuminance on surface (2Unit-sphere method, Method 1)

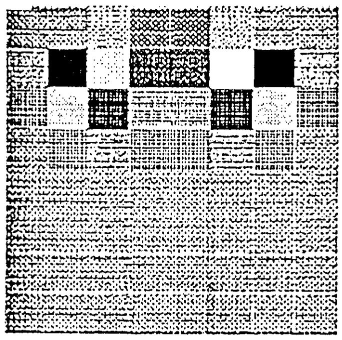

Fig. 7(b) Initial illuminance on surface 2(Unit-sphere method, Method)

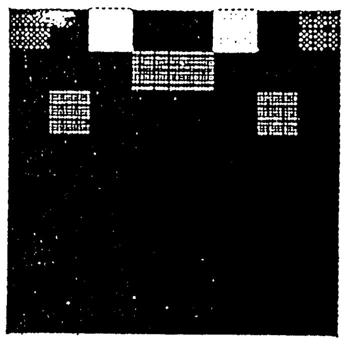

Fig. 8(a) Initial illuminance on surface 2(Boundary integral method, Method 1)

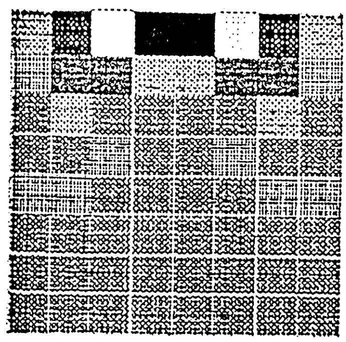

Fig. 8(b) Initial illuminance on surface 2(Boundary integral method, Method 2)

Figure 9 and 10 are the final illuminance on the floor surface. Figure 9 is equivalent to Figure 7 and Figure 10 is equivalent to Figure 8. The result of the final illuminance in the floor that the kinoform is not installed on the window is shown in Figure 11 to compare with the result that the kinoform is installed. The incident angle of Figure 9, 10, and 11 is $\theta = 45°$, $\phi = 28°$

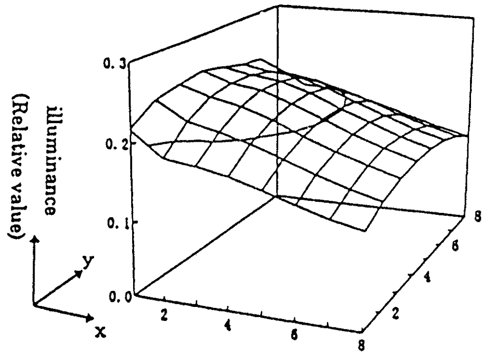

Fig. 9(a) Final illuminance on surface 1 (Unit-sphere method, Method 1)

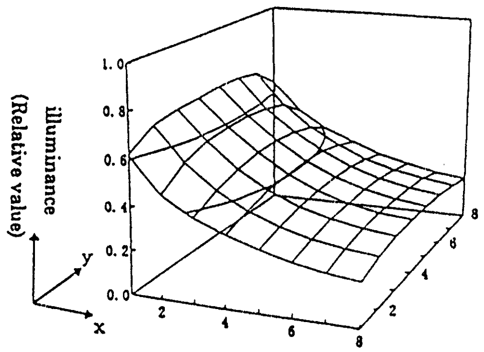

Fig. 9(b) Final illuminance on surface 1 (Unit-sphere method, Method 2)

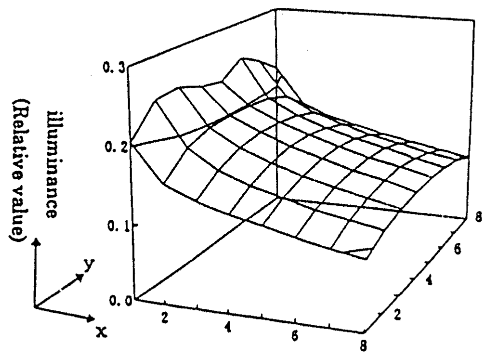

Fig. 10(a) Final illuminance on surface 1 (Boundary integral method, Method 1)

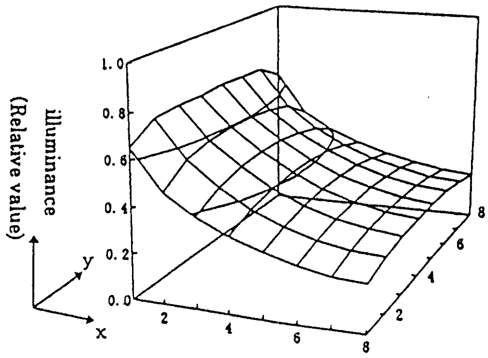

Fig. 10(b) Final illuminance on surface 1 (Boundary integral method, Method 2)

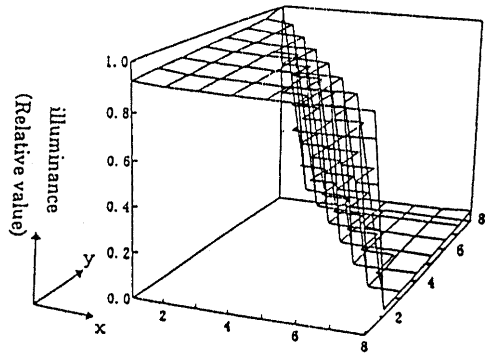

Fig. 11 Final illuminance on surface 1 (Kinoform is not installed)

The averages of illuminance and the standard deviations of illuminance on the floor surface are shown in Table 2 and 3, respectively. The averages of illuminance in Table 2 are relative values on the floor surface on the occasion that the illuminance of the light incidented on the kinoform surface is 1. The standard deviations of illuminance in Table 3 are relative values on the floor surface on the occasion such that the standard deviation of the average illuminance is made 1.

6. Conclusion

Table 2 shows that the averages illuminance are almost constant values in each case.

Method 2 gives intenser illuminance than by Method 1 in both cases of unit-sphere method and boundary integral method.

Table 3 shows that the standard deviations are almost constant values in each case, too.

Method 1 gives higher uniformity than Method 2 in both cases of unit-sphere method and boundary integral method.

Table2 Averages of the final illuminance on surface 1

		unit-sphere method		boundary integral method	
		Method 1	Method 2	Method 1	Method 2
Θ	Φ				
standard					
90	0	0.184015	0.400905	0.150969	0.391115
vernal・autumnal equinox day					
30	19	0.189575	0.398079	0.152363	0.288992
45	28	0.189496	0.398079	0.152409	0.388035
60	37	0.190075	0.397324	0.155915	0.389516
75	46	0.189458	0.397324	0.153244	0.389323
90	55	0.189129	0.397955	0.151679	0.389492
the summer solstice					
30	42	0.188484	0.398832	0.154140	0.389298
45	51	0.189310	0.397152	0.152241	0.388760
60	60	0.189082	0.397162	0.152865	0.389476
75	69	0.188882	0.396829	0.152865	0.389379
90	78	0.189034	0.398586	0.152249	0.389099
the winter solstice					
30	0	0.187044	0.397404	0.152921	0.388334
45	6	0.189035	0.398260	0.155697	0.389596
60	12	0.189885	0.398854	0.152936	0.388803
75	24	0.188262	0.398481	0.150142	0.389379
90	30	0.189872	0.396931	0.153208	0.388641

Table3 Standard deviations of the final illuminance on surface 1

		unit-sphere method		boundary integral method	
		Method 1	Method 2	Method 1	Method 2
Θ	Φ				
standard					
90	0	0.168274	0.397625	0.239930	0.388108
vernal・autumnal equinox day					
30	19	0.176473	0.394843	0.260653	0.387846
45	28	0.177059	0.398639	0.243667	0.385949
60	37	0.179166	0.394667	0.261738	0.388669
75	46	0.177157	0.394832	0.261543	0.388643
90	55	0.175076	0.398235	0.260602	0.387771
the summer solstice					
30	42	0.175044	0.393128	0.261054	0.387317
45	51	0.176086	0.393154	0.261063	0.391138
60	60	0.178388	0.393214	0.257710	0.388260
75	69	0.175527	0.393214	0.248927	0.387319
90	78	0.175751	0.395952	0.249380	0.387950
the winter solstice					
30	0	0.169569	0.395934	0.244269	0.386249
45	6	0.176406	0.396439	0.251379	0.389205
60	12	0.174189	0.401309	0.258349	0.388510
75	24	0.174469	0.396234	0.247958	0.387319
90	30	0.177140	0.393453	0.244484	0.388059

If we make the kinoforms which the phase difference is considered for each incident angle, we can get almost uniform illuminance distribution on the floor surface.

From Figure 9, 10, and 11, the case that the kinoform is installed is better than the case that the kinoform is not installed.

The case that the kinoform is installed is better than the case that the prism is installed, too.

From the above, despite of the minus illuminance is dealt with in Method 1 and 2, the final illuminance on the floor is improved fairly when the kinoform is installed on the window.

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