Contribution of Horizontal Louvers to the Daylight Distribution in a Large Multipurpose Hall

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Abstract

Daylight distribution in a large multi-purpose hall with complex geometry was analyzed using computer simulations under a limited number of daylight conditions. Daylight conditions included clear glazing with no louvers, horizontal louvers, and louvers positioned at a 45° under a clear sky at 10:00 AM of the day and year. Average daylight illuminance on each indoor surface was determined for given daylight conditions. Illuminance levels on surfaces were impacted critically by the louver conditions. The daylight illuminance on floor changed significantly as the calculation point moved back from the east-facing window. The contribution of louvers to the daylight distribution was provided. The louvers reduced the daylight up to 44.93% as compared with that of the no louver condition. The correlation between the illuminance on eastside window surface and on indoor floor was calculated using linear regression in order to predict impact of louver to floor illuminance. The $r^2$ values ranged from 0.6066 to 0.9230 according to louver angle. The daylight distribution by ray diagrams and a computer rendering image were presented to show how each surface was impacted by the daylight according to different louver conditions under different season.

Keywords: Daylight Illuminance, Daylight Distribution, Louver Condition, Raydiagram

1. INTRODUCTION

Generally, electric lighting system is used to illuminate the interior building. Sustainable and green building design strategies increasingly require more use of natural daylight, which can contribute to the electric lighting system control and human comfort. The daylight distribution significantly depends on the façade design, shading device conditions, building location, day and time. In order to apply properly natural daylight through fenestration systems, the prediction about it illuminance should be determined. The exact prediction of daylight for given conditions supplies strong foundation to the application of electric lighting control system using daylight as an important light source, since the position, viewing angles of a photosensor and illuminance levels on each surface affect the control application critically.

Many researchers performed measurements and computer modelings for daylight availability in buildings providing useful information (Love, 1993; Navvab, 1998; Johnsen, 1998; Bellia, 2000, Li, 2000). This paper expands on previous works, applying more complicate building geometry with three louver conditions on east façade so as to predict daylight distribution in space where lighting control system can be applied. In this study, computer simulations were performed for a large multipurpose hall under a limited number of daylight conditions.

2. COMPUTER SIMULATION

(1) Limitation of Simulation Software (Autodesk, 1996; Ashdown, 1994)

The simulation software used in this research was the LightScape, which has two main algorithms. One is the local illumination algorithm, which describes only how individual surfaces reflect or transmit light. The other is global illumination algorithm applying ray-tracing and radiosity theory.

The conventional ray-tracing technique allows us to model the direct illumination using the inverse square law. This algorithm assumes that any light fixture with area source is divided into a finite two-dimensional array of ‘k’ point source. Each point source should be visible from the surface, and the intensity of a light source for each direction should be provided. The distance between the source and surface should be determined exactly. Although the ray-tracing models many rays, it presents very little part of rays belong to the field of light in real space.

A partial solution about the visibility is the backward ray-tracing that traces the rays of light backward from the eye position to the each surface where it is originated from in space. The ray at the point of intersection comes from both direct ray from the light source and indirect ray from the surface where multiple reflections occur between many surfaces and objects.

This reveals the shortcoming of ray-tracing modeling techniques. All reflections from surface cause an infinite number of rays from a single arriving ray. This modeling approach takes sample those rays at the surface, but the total sample size of the rays coming from reflections decreases according to the geometric conditions. So, ray-tracing techniques do not provide enough evidence to model light transfer at a particular point in space because all surfaces contribute to illuminance level in space.

Radiosity theory starts assuming that all surfaces are divided into a single element called a patch. It is assumed that the single surface is a Lambertian reflector and the light source is a Lambertian emitter. Since the Lambertian surface generates constant luminance to all viewing direction, the angle of incident flux is not critical to the view of a single patch. Other assumptions are each patch has uniform exitance and intervening medium is nonparticipating.

In this theory, the distribution of flux emitting the Lambertian surface is calculated using the Lambert’s cosine law and radiosity equations are used for the final computation. Radiosity theory improves the accuracy of modeling since the contribution of entire photic field is considered at all points in space. However, current
Radiosity methods are confined to model purely reflective space. The refraction of light through material, scattering, diffraction, and other sophisticated optical phenomena are not considered. In conclusion, neither radiosity nor ray-tracing offers a complete solution for simulating all illumination effects such as refracted, scattered, diffracted or whatever by one or more objects.

However, the shortcoming of Lightscape was proven by a research (Renfro, 1999). It was performed to test the accuracy of Lightscape calculation in measuring daylight. It compared the data collected from a physical scale model and from a computer simulation in an open site under clear sky conditions. It proved that the testing by Lightscape with direct sun was accurate when indirect light from the north sky was significantly different.

Another shortcoming in Lightscape is the apparatus used for modifying sky conditions, currently it is a slide that ranges sky conditions between zero(0) representing a cloudless sky to one (1) representing full overcast sky. This in turn allows only two distinct options either clear or full overcast sky conditions. Finally it was concluded that “Lightscape is accurate enough for qualitative lighting analysis, provided care is taken in the modeling stage, however a correction factor may be devised to adjust illumination data for this method of calculation” (Shalaby, 2002)

(2) Room and Daylight Conditions

The multipurpose hall used in this study was 100ft long and 56ft wide. The ceiling height was 45ft for east side and 30ft for west side. The reflectance of ceiling, wall and floor was assumed to be 0.8, 0.5, and 0.2 respectively. The entire areas of north and eastside of the space were windows. The ratios of window to wall for west and south side were 46.6% and 37.3%. It was assumed that the reflectance of all windows was 0.4. Mullions were considered for all windows and their width was two inches.

The shading device conditions were no louver (clear glazing), horizontal louvers oriented at 0°, and 45° applying the louver reflectance of 0.82. It was assumed that the louver was installed only on east side for all computer simulations. The louver covered 2/3 of the east-facing window from the top. Overhangs were considered for all directions. Figure 1 represents the dimension of the space used in this research.

The site for this building was assumed to be Detroit, MI (Latitude: 42° 38', Longitude: 83° 10'), U.S.A. Clear sky was applied with a ground reflectance of 0.2. The days modeled were December 21, March 21, and June 21. Since the louver was located on east-facing window and this research aims at investigating its impact by louver installed on east side window to indoor daylight distribution, the time for the simulation was assumed to be 10:00 AM for each day. Selecting 10:00AM, this research covers the sun altitude which was 18.7°, 39.37°, 58.85° and the azimuth angle varying from 28.87 to 62.68° which possibly represents the lower and higher sun altitude where the sun is a light source that causes illuminance on east-facing window under a series of daylight conditions. Electric lighting was not considered. Table 1 summarizes daylight and louver conditions used in this study.

3. SIMULATION RESULTS

(1) Average Daylight Illuminance on Indoor Surface

Figure 2-Figure 5 present the average daylight illuminance on inside surface according to the three louver conditions for each month. Overall, the illuminance levels varied significantly according to the louver conditions. The illuminance levels for no louver condition showed higher values than those of other louver conditions. The interesting thing was the 45° louver condition provided higher values than horizontal louver condition for all indoor window surfaces.

Window illuminance levels showed various change patterns as the solar altitude and louver conditions changed. The average illuminance level on the north-facing window showed the highest value in December. The north-facing window showed the most significant change range among other windows as the month changed. When the month changed from December to June, the changed illuminance levels were 4749.51 lx for no louver, 3837.09 lx for horizontal louver, and 4449.67 lx for 45° louver condition.
While north-facing window showed significant change of illuminance on its surface, the west-facing window showed the most narrow change range among others. The south-facing window showed the highest values for all louver conditions in March and June. In March, they were 6615.22lx for no louver, 5514.37lx for horizontal louver and 5897.07lx for 45° louver condition.

It is inferred that the direct component from the sun passed through the louvers and reached the north-facing window because of the lower solar altitude and azimuth in December. As a result, it caused high illuminance level. On the contrary, the direct sun did not affect the illuminance level on the north-facing window in June because the louver contributed effectively to block the direct sun with high altitude.

Since the louvers were tilted by 45° upward and allowed more daylight to pass through, the illuminance levels on the floor for the 45° louver condition were higher than those of horizontal louver condition for each month. The differences between them were 1954.5lx in December, 3435.87lx in March and 3005.84lx in June.

It is thought that the louvers blocked the direct components from the sun and sky changed by atmospheric conditions and they bounced back the arriving daylight to the inside space. This generated much more interreflection between indoor surfaces and finally affected the floor illuminance level. This result implied that the daylight available inside space was strongly impacted by the louver control under changing solar altitude. When no louver was considered, illuminance levels increased as solar altitudes increased. But, for the horizontal and 45° louver conditions, March showed the highest level for all months assumed.

Unlike the case of floor, the illuminance levels on ceiling for no louver condition increased and decreased again as the sun moved from lower altitude to higher altitude. Due to the direction of tilt angle of louvers, 45° tilted louvers allowed more daylight to pass through than the horizontal louvers did. March showed the highest illuminance level for each louver condition. They were 5768.42lx for no louver, 4597.36lx for horizontal louver and 4948.52lx for 45° louver condition.
Table 2 — Ratio of illuminance on each indoor surface as compared with no louver condition (unit: %)

<table>
<thead>
<tr>
<th>Louver Conditions</th>
<th>Dec. 21</th>
<th>Mar. 21</th>
<th>June. 21</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hor 45°</td>
<td>73.66%</td>
<td>66.55%</td>
<td>63.25%</td>
</tr>
<tr>
<td>Hor 45°</td>
<td>84.99%</td>
<td>82.53%</td>
<td>60.04%</td>
</tr>
<tr>
<td>Hor 45°</td>
<td>84.93%</td>
<td>83.36%</td>
<td>65.51%</td>
</tr>
<tr>
<td>Hor 45°</td>
<td>87.38%</td>
<td>89.77%</td>
<td>73.88%</td>
</tr>
<tr>
<td>Hor 45°</td>
<td>75.94%</td>
<td>95.49%</td>
<td>44.93%</td>
</tr>
<tr>
<td>Hor 45°</td>
<td>83.43%</td>
<td>79.70%</td>
<td>61.67%</td>
</tr>
<tr>
<td>Floor</td>
<td>75.94%</td>
<td>95.49%</td>
<td>44.93%</td>
</tr>
<tr>
<td>Ceiling</td>
<td>83.43%</td>
<td>79.70%</td>
<td>61.67%</td>
</tr>
</tbody>
</table>

Figure 6. Ratio of Average Horizontal Illuminance on Indoor Floor to Outdoor Horizontal Illuminance

Figure 7. Ratio of Horizontal Illuminance on Floor to Outdoor Horizontal Illuminance according to the Distance from the East-facing Window

Figure 8. Ratio of Ceiling Illuminance to Outdoor Horizontal Illuminance according to the Distance from the East-facing Window

(2) Daylight Illuminance Distribution

Figure 6 shows the ratios of horizontal illuminance on indoor floor to the illuminance on outdoor ground according to louver and month conditions. As the solar altitude increased the ratio decreased for all conditions. The ratios for December were higher than the ratios for March and June. The horizontal louver condition provided the lowest ratios among three conditions. The ratio in March ranged from 12% to 17.64%. The interesting factor was that the ratios for horizontal and 45° in June were below 10%.

Table 2 represents the ratio of the daylight illuminance when horizontal and 45° louvers were considered to the daylight illuminance when no louver was assumed. Overall, the values decreased for horizontal and 45° louver conditions as month changed from December to March and June. For horizontal louver condition, the value for the floor illuminance changed significantly. These values provide how much the control of louver contributed to the daylight distribution in the space. The values ranged from 44.93% to 95.49% which means that the louver can reduce the daylight by 44.93%.

This result indicates that the contribution of louver to the daylight distribution in the space was much less effective when the solar altitude was high. The horizontal and 45° louver allowed daylight to pass through easily and contributed to the daylight gain when the sun had lower altitude. Therefore, the more sophisticate control strategy of shading device is required to cope with the direct daylight when solar altitude is low.

Figure 7 shows the average ratio of indoor horizontal floor illuminance to outdoor horizontal illuminance for each month and louver condition according to the distance from the east-facing window where louvers were installed. In general, the distribution in December affected by the lower solar altitude which was 18.7° provided relatively even distribution compared to that of March and June showing up to 58.85° sun altitude.

The ratios for all cases decreased showing the ratio from 64.88% to 0.97% as the distance increased from the east-facing window since the direct sun showing different altitude for each season influenced near the window area significantly and did not reach the floor deeply as described in Figure 9 - Figure 11.

For the area which is 10ft away from the window represents noticeable ratio difference between no louver condition and horizontal louver condition for all months. The difference was 15.45% for December, 24.62% for March and 38.36% for June. As described in Figure 9 - Figure 11, the area was impacted by first reflected distribution from the backside under no louver condition and influenced by part of reflected daylight from backside.
and louvers in December. In March, the area did not receive first reflected influence from the indoor surface. Beyond this point, the difference for March and June were less than 3.17%. However, in December the difference was 9.26% for the point 20ft away from the window.

The ratio difference between no louver and 45° louver condition at the area which is 10ft away form the window in December and March showed lower than 1.65% since the 45° louver condition reflected back the daylight to the floor area. On the contrary, the difference in June was 23.77%, since much more direct daylight compared to December and March reached the area for no louver condition due to the increase of sun altitude, but the 45° louver controlled the daylight and sent the reflected light to the floor area as described in Figure 11.

This result indicates that the area near window where louvers were installed can be critically influenced by the contribution of louver redirecting the daylight distribution under different daylight conditions. However, the contribution of louver to the daylight distribution beyond 20ft from the window where the direct sunlight penetrated did not show noticeable difference pattern for louver conditions. This result potentially suggests which area will be critical and effective in applying an automatic control system, such as daylight dimming system, to the space.

Figure 8 shows the distribution of average ratio of illuminance on ceiling to outdoor horizontal illuminance according to the distance from the east-facing window. The curve-shaped ceiling area divided equally into 12 elements in order to perform simulations. For the computational purpose, the illuminance levels for each two elements were calculated and their mean values were used. P1 represents the two divided elements nearest the east-facing window and P6 means the two elements farthest away from the east-facing window.

Unlike the case of floor, there were no significant chang ingover points. As the elements moved away from the window, the slope of reduction was not very steep for all cases and the range of ratio difference among louver conditions became stable. The ratio in December showed higher distribution than other cases. It ranged from 12.63% to 10.84% for the horizontal and from 8.31% to 5.24% for 45° louver conditions.

This result was because the first reflected components from the louver reached different areas and became the source of inter-reflection in the space, since incoming component was controlled by the louver conditions and passed through or bounced back to the inside space again. The different area affected by the direct component and reflection from the louvers caused the different ratio distribution under the assumed daylight condition. So, the areas affected initially by the reflection from the louvers should be considered critically when lighting control issues arise.

(3) Statistical Analysis between Illuminance on Outside Window Surface and Inside Floor

### Table 3. Coefficient of Determination($r^2$) between Outdoor Illuminance on East-facing Window and Indoor Floor Illuminance

<table>
<thead>
<tr>
<th>Louver Condition</th>
<th>Month</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dec. 21</td>
<td>Mar. 21</td>
<td>June. 21</td>
</tr>
<tr>
<td>No</td>
<td>0.7419</td>
<td>0.6066</td>
<td>0.8568</td>
</tr>
<tr>
<td>Horizontal</td>
<td>0.7988</td>
<td>0.8419</td>
<td>0.6479</td>
</tr>
<tr>
<td>45°</td>
<td>0.7503</td>
<td>0.9231</td>
<td>0.7796</td>
</tr>
</tbody>
</table>

The coefficients of determination ($r^2$) between the illuminance on east-facing window surface and on indoor floor were determined using a linear fit between those two quantities in order to predict how the outside window illuminance controlled by different louver condition under different daylight conditions impacts the floor illuminance.

The $r^2$ values ranged from 0.606 to 0.9231 according to louver angle. It implied that the total variation associated with the use of outdoor illuminance on eastside window reduced by 0.606 for no louver condition and by 0.9231 for 45° louver condition in March.

(4) Ray Diagram and Rendering Images

The ray diagrams and rendering image in Figure 9- Figure 12 provide visual explanation for the different daylight distribution for each louver condition and month. Overall, the ray diagrams indicate that the direct and reflected components from the sun, sky and louvers impact different area of the space. While the horizontal louvers bounced back the incoming ray to the ceiling area, 45° louvers reflected the incoming ray to the floor.

For no louver conditions, the area affected by the direct components moved toward the east-facing window as the month was changed from December to June. The entire floor area was covered by the first reflected components from the west-facing window in December.

Regarding the horizontal louver conditions, most of the ceiling area was impacted by the reflected components from the louver in December. The half of the ceiling area received reflected components from the louver in March. The area of floor ranging from 7ft to 22ft away from the east-facing window was impacted by the reflected component in June. The 45° louver condition in March allowed the incoming daylight to pass through the louver and arrive at the center area of the floor. 82.3% of the floor area received direct and reflected components from the louvers in June.

The ray diagrams showed the importance of louver angle in order to control the direction of direct and reflected daylight into the space according to the changing solar altitude. The different daylight distribution discussed here provides basic foundation for which areas of surfaces are affected by the daylight directly or indirectly through the controlled louvers.
Figure 9. Sun Ray Diagrams (December 21st, No, Horizontal and 45° louver, from left)

Figure 10. Sun Ray Diagrams (March 21st, No, Horizontal and 45° louver, from left)

Figure 11. Sun Ray Diagrams (June 21st, No, Horizontal and 45° louver, from left)

Figure 12. Rendering Image (December 21st, Horizontal Louver)
4. CONCLUSION

In this study, computer simulations using the Lightscape were performed for a large multipurpose hall under limited numbers of daylight conditions. A summary of general findings of this study is as follows:

(1) Daylight distribution on inside surfaces for each given louver condition and solar altitude under clear sky was provided. Daylight illuminance levels on each inside surface showed critical difference according to the louver angle and solar altitude. The ratio of horizontal illuminance on floor to outdoor horizontal illuminance changed significantly as calculation points moved back from the east-facing window. The ratios on the area near east-facing window were affected critically. Starting from 20ft away from the east-facing window, the ratios in December were higher than those calculated for March and June. This result potentially provides which area on the floor would critically contribute to the lighting control strategy and where the photosensor would be placed when a daylight control system is applied to the space under a variety of daylight conditions.
(2) The contribution of horizontal louvers to the daylight distribution was provided. The lovers reduced the daylight up to 44.93% when it was compared to the no louver condition. The ratio of horizontal indoor illuminance to outdoor illuminance was provided according to the change of louver conditions and they varied between 6.80% and 29.26%. Since the lower altitudes provided higher ratio for all louver conditions due to the direct sun, it would be necessary to develop a more delicate strategy for controlling the daylight from the lower sun angle.

(3) The coefficients of determination between the illuminance on east-facing window surface and on indoor floor were provided using a linear regression under a limited daylight and louver conditions. They implied that the variation associated with the use of outdoor illuminance on east-facing window reduced by each different amount according to louver condition under daylight conditions.

(4) The distribution of daylight by ray diagrams and a image by the Lightscape simulations were presented. This result indicated how each surface was impacted by the direct sunlight according to each different louver condition under different solar altitudes. The diagrams supplied fundamental prediction where the first and secondly impacted area from the direct sun and reflected components from the louvers would be.

5. STUDY LIMIT AND FUTURE WORKS

Since this study was performed using only one computer simulation software which adapted limited calculation algorithms, the calculation results might not be as exact as the results from other computer simulations which consider specific atmospheric conditions such as air turbidity, condensing water thickness. In addition, the daylight conditions assumed in this research were confined. Therefore further research using softwares with advanced algorithms should be required to provide more reliable results.

A field study would help to further validate these results, but could not be performed as part of this study due to limitations. Additional work is necessary to study the effects by more detail angle of louver. More work should be carried out to investigate if the daylight distribution in this study could be applied to the room where similar shading devices are installed. The results of this study only suggest with caution that the presence and the control of louver angle.

REFERENCES