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LIGHT SCATTERING FENESTRATION SYSTEM

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Abstract: Successful integration of day lighting systems requires the ability to predict their performance for given climates. In this, a bottom-up approach is applied to evaluate the optical performance of a selection of day lighting systems. The evaluations are based on the optical properties of the included materials, and focuses on developing new optical characterization methods. The work on characterization techniques uses an integrating sphere method to characterize the transmittance of light scattering samples more accurately. The method's principle is to reduce the discrepancy in light distribution between the reference and the sample scans by using an entry port beam diffuser. For samples exhibiting distinct light scattering patterns, the benefits of improved uniformity outweigh the errors introduced by the diffusing material. The method is applicable to any integrating sphere instrument, and its simplicity makes it suitable for standard measurements.

Keywords: Venetian blind slat, ABg -model, ray tracing simulation

I. INTRODUCTION

To determine the daylighting implications of light scattering fenestration systems, such as Venetian blinds, knowledge of their light distribution is necessary.

It is essential that these light scattering data are expressed using a common format that can be accepted by most solar energy and daylighting calculation software.

There is a consensus in the use of the BSDF as a standardized format [1, 3, 8, 9], and an important step forward was the acceptance of BSDF data in the Radiance daylighting simulation software [2].

A work flow for creating and applying BSDF data for daylighting simulations has been described [10], and the work on developing metrics based on BSDF data has started [11].

More research on both characterization and software implementation is, however, needed before the use of BSDF data becomes common place in daylighting simulations [1].

This includes population of complex glazing databases (CGDB), such as the CGDB associated with Window6 [5], with a wider range of products and doing so involves standardizing the procedures for obtaining BSDFs.

If accurate measurements are possible, this is the preferred method.

However, as was noted in the experimental section, measurements can be time consuming, associated with significant errors, and notable to produce full BSDFs.

Comparison between radiosity based and ray tracing based methods have shown good agreement for blinds with diffuse properties [12], but radiosity methods cannot be used for materials with a large specular component.

Ray tracing methods are promising since they can handle both specular and diffuse properties, but they require the input of optical data.

Andersen et al. [13] evaluated a venetian blind system using hemispherical optical data for the slats

2. THEORY:

2.1. Venetian blind slat:-

An outline of the method used for ray tracing of the Venetian blind system is presented in figure 1. First, the optical properties of the individual slats were measured as detailed as possible.

The measurements included hemispherical reflectance, at normal and oblique incident angles, and in-plane light 75 scattering. Secondly, the ABg-model light scattering model, was fitted to the measured data and used to describe the optical properties of the slats in the ray tracing program.

The geometry of the slats and the distance between the individual slats were also provided as input to the ray tracing simulations.

The output from the ray tracing simulations were transmittance and reflectancescattering distributions as a function of incident angle.

These scattering distributions were integrated to obtain the hemispherical transmittance and reflectance for the system.

Figure1. A schematic drawing presenting the work flow for the characterization of a Venetian blind system.

The optical properties of the individual slats are determined using hemispherical and goniometric measurements. This information is condensed using the ABg-model and used as input for the ray tracing simulations of the Venetian blind system.

2.1 Optical properties of a Venetian blind slat

The total and diffuse reflectance were determined for both sides of the slat, as shown in figure 3, in the solar range (300–2500 nm).

The white side of the slat is almost entirely diffuse in the visiblewavelength range, but it becomes more specular in the near-infrared. At 2500 nm the specular component is almost 12%. The silver colored side of the slat is, as expected, more specular than the white side of the slat. However, the brushed

properties of the aluminum gives rise to scattering and explains the diffuse component of the silver side.

The hemispherical reflectance was also determined as a function of incident angle using a center mount accessory [4]. Two reference plates were used for the measurements; a specular aluminum plate was used for the silver side of the slat and a diffuse white spectralon plate was used for the white side of the slat. The resulting hemispherical reflectance is presented in figure 4.

For the silver side of the slat, two of the measurement points, at 45° and 55°, clearly deviate from the curve. For these angles, the beam from the specular reference scan is reflected off the edge of the reference exit port shown in figure 2.

Figure 2: Schematic top-view of an integrating sphere for transmittance and reflectance measurements in a double beam instrument. For transmittance

measurements the sample is positioned across the transmittance port. Diffuse reflectance and transmittance can be measured by opening the

specular reflectance exit port (for reflectance) or the reflectance port (for transmittance). The rectangle and the circle in the center of the sphere represent a photomultiplier tube and a PbS cell, respectively. These detectors are mounted in the bottom of the sphere and used for detection in the integrating sphere from Labsphere.

The anomalously high measurement signal is thus most likely caused by increased absorption at the port edge for the reference scan. The diffuse properties of the white side of the slat spread the reflected light over a larger area and the signal reduction due to the exit port is less pronounced.

Figure 3: Hemispherical reflectance properties at normal angle of incidence for the silver and white colored side of the slat. The white side is predominantly diffuse, whereas the silver colored side of the slat has a specular component

Figure 4: Hemispherical reflectance at 633 nm as a function of incident angle for the silver and white sides of the slat.

The light scattering properties of the Venetian blind slat were also determined using a goniospectrometer. The in-plane scattering is presented for a few incident angles, θ_{in} , in figure 4 using the BRDF as a function of outgoing angle, θ_{out} . The specular reflection of the silver colored side of the slat can be noted, and it

is also seen that the white side of the slat becomes more specular with increasing incident angle.

3. EXPRESSING OPTICAL PROPERTIES USING THE ABG-MODEL:-

The A, B, and g parameters, were fitted to the experimental data using the ABg-model. Accurate ray tracing requires that the light scattering properties are accounted for in the software's description of the optical properties. In Trace the use of the ABg-model makes it possible to present large amount of light scattering data using only three parameters. The model, proposed by Freniere [6] as an application of Harvey's work on light scattering [7], uses the linear

shift-invariant representation $(|\vec{\beta} - \vec{\beta}_0|)$. This means that the BSDF solely depends on the absolute difference

between the projection of the scattering direction ($\vec{\beta}$) and the projection of the specular directions ($\vec{\beta}_0$) onto the sample plane, as seen in figure 5. The advantage of the representation is that the BSDF becomes independent of incident direction according to

$$BSDF\left(|\vec{\beta} - \vec{\beta}_0|\right) = \frac{A}{B + |\vec{\beta} - \vec{\beta}_0|^g} \dots \dots \dots (1)$$

where A, B, and g are empirically determined parameters. The parameters do not originate from physical properties, but their effect on the fitted

curve is worth mentioning. In the specular direction, i.e. when $(|\vec{\beta} - \vec{\beta}_0|)=0$, the intensity is given by the ratio A/B. The parameter g, describes the specularity of the sample and a higher value of g indicates a more pronounced specular peak. A perfectly diffuse, Lambertian, sample would hence have $g = 0$. The BSDF is frequently presented using a logarithmic scale due to the wide range of intensity values. When a logarithmic scale is used in combination with the ABg-model, g is the slope of the curve, and B determines the roll-off point between the specular plateau, A/B, and the slope, g.

Figure 5: Definition of $\vec{\beta}$ and $\vec{\beta}_0$, used for angular representation in the ABg-model. Incident light with the direction $\hat{r}_i$ is reflected off the surface, with normal $\hat{n}$, in the specular direction $\hat{r}_s$ and the scattered direction $\hat{r}$. $\vec{\beta}$ and $\vec{\beta}_0$ are given as the projection onto the surface of the directional vectors, $\hat{r}$ and $\hat{r}_s$, respectively

For the fit, the goniometric data provide information about the light scattering distribution and the hemispherical data ensure that the total integrated intensity is maintained. The ABg-model is best suited for light scattering and the A, B, and g parameters

were fitted to the diffuse part of the data whereas the specular component was added separately. An example of the fit is shown for an incident angle of 40° in figure 5 for the two sides.

Figure 6: Measured in-plane BRDF for four different angles of incidence, θ_{in} . a) for the silver colored side of the slat, and in (b) for the white side of the slat.

In this figure, the added specular component corresponds to the area between the fitted and the experimental curve. It should be noted that both the x-axis and the y-axis in figure 6 are presented on

logarithmic scales, and the specular component of the silver side of the slat is approximately one order of magnitude greater than that of the white side.

Figure 7: Example of fit of A, B, and g parameters to goniophotometric data at $\theta_{in}=40^\circ$. The B and g parameters were determined to be constant for both the silver ($B = 4.8 \cdot 10^{-3}$, $g = 1.9$) and the white side ($B = 1.0$, $g = 0$), in (a) for the silver colored side and in (b) the white side.

When fitting the ABg-model to the diffuse part of the scattering, the B and g parameters become independent of the angle of incidence. For the silver side of the slat, B was determined to be $4.8 \cdot 10^{-3}$ and g to be 1.9. The broader specular peak and diffuse properties of the white side of the slat results in a higher value of the B parameter, 1.0, and Lambertian fit of the g parameter, i.e. $g = 0$. The values of the specular component R_{spec} and the A parameter are given for the silver side of the slat in figure 7(a) and the white side of the slat in figure 7(b).

It should be noted that the four graph areas are presented with different ranges on the y-axes. For the silver side of the slat, the ABg-model alone is sufficient to describe the scattering distribution at larger incident angles and the R_{spec} component approaches zero. In figure 7(b), it can be seen that the opposite is true for the white side of the slat, where the specular component increases with incident angle. This can be related to the increasing specularly that was noted for the measured data in figure 8(b).

Figure 8: The angle dependent A and R_{spec} parameters as fitted to the optical properties of the slat. The B and g parameters were determined to be constant for both the silver ($B = 4.8 \cdot 10^{-3}$, $g = 1.9$) and the white side ($B = 1.0$, $g = 0$), in (a) for the silver colored side and in (b) for the white side.

The A , B , and g parameters were also fitted using only the integrated hemispherical reflectance values of the slat. This provided a second set of fitting parameters that do not account for angle dependent variations. Both sets of parameters were used to describe the surface properties of the Venetian blind system in separate ray tracing simulations. The Venetian blind system with angle dependent properties is referred to as Angular and the system with Lambertian scattering properties is denoted Lambertian.

4. RAY TRACING OF THE VENETIAN BLIND SYSTEM:-

The Venetian blind system, consisted of five equally spaced slats mounted with the convex side facing up and a slat-to-slat distance of 21 mm. The number of slats were chosen to minimize the computation time, while insuring that no rays would pass on either side of the shading system. In figure 7, a schematic drawing of the angles defining the Venetian blind system is presented.

Figure 9: Schematic illustration of the direction angles θ and ϕ , which describe the direction of the light and the tilt angle β . θ is the angle between the projection onto the xy -plane and the incident light and ϕ is the direction determined in the xz -plane.

For the ray tracing, the Venetian blind system was positioned in the center of a virtual detector sphere

and one million rays were emitted from each hemispherical patch.

5. RESULTS

The results from the ray tracing simulations are presented using integrated values and light scattering distributions represented by hemispheres. The integrated values are useful for a basic comparison and can also give an indication of the system's performance, but they do not provide any information about the light redirecting properties of the Venetian blind system. The light scattering distributions, on the other hand, provide detailed information about the intensity and direction of the light transmitted or reflected by the system. Presenting all the data using this representation is however not feasible given that it would require 1740 (145 incident directions $\times$ 6 tilt angles $\times$ 2 sets of ABg parameters) hemispheres for transmittance and 1740 hemispheres for reflectance.

In figure 10 and 11, the integrated values are presented for six tilt angles from 0° (horizontal slats) to 75° for the Angular and Lambertian systems, respectively. It can be noted that the Venetian blind system with angular properties has a generally higher transmittance and lower reflectance than the system with Lambertian properties.

This can be related to the specular properties of the silver side of the slat, which redirects more of the light to the interior side.

The two systems have similar reflectance properties for 60° and 75° tilt angles. For these tilt angles the white side of the slat faces the incident light, and its diffuse scattering can reasonably well be approximated by Lambertian properties.

Figure 10: Integrated solar properties for Venetian blind with Angular fit of slat properties, slat tilt angles from 0° to 75°, and incident angle $\phi = 270^\circ$, in (a) R_{sol} and in (b) T_{sol} .

Figure 11: Integrated solar properties for Venetian blind with Lambertian fit of slat properties, slat tilt angles from 0° to 75°, and incident angle $\phi = 270^\circ$, in (a) R_{sol} and in (b) T_{sol} .

The light scattering hemispheres are presented in figure 12 and 13 for the Angular and Lambertian system, respectively. An incident angle of 30° and a horizontal slat was chosen for reflectance, and an incident angle of 60° and a tilt of 30° for

transmittance. In transmittance, there is a significant difference in both intensity and distribution between the two systems. The light distribution in reflectance is similar for the angular and the Lambertian systems, but the difference in intensity is significant.

Figure 12: Virtual hemisphere projections for Venetian blind with *Angular* fit of slat properties, in (a) BRDF [sr-1] at incident angles $\theta = 30^\circ$ and $\varphi = 270^\circ$, and tilt=0°, and in (b) BTDF [sr-1] at incident angles $\theta = 60^\circ$ and $\varphi = 270^\circ$, and tilt=30°.

Figure 13: Virtual hemisphere projections for Venetian blind with *Lambertian* fit of slat properties, in (a) BRDF [sr-1] at incident angles $\theta = 30^\circ$ and $\varphi = 270^\circ$, and tilt=0°, and in (b) BTDF [sr-1] at incident angles $\theta = 60^\circ$ and $\varphi = 270^\circ$, and tilt=30°.

6. CONCLUSIONS AND FUTURE WORK

A method for optical characterization of a Venetian blind system using a combination of optical measurements and ray tracing is presented. The individual slats of the investigated system had a combination of specular and diffuse properties, and were modeled using two sets of fitting parameters. One simplified approach assumes Lambertian properties of the slats and the second approach is based on the measured angular data. An extensive comparison of the scattering distribution for the two fits is impossible to make, but a couple of combinations of incident direction and tilt are

compared. These showed that there are significant differences between the two fits, indicating that more detailed optical data are necessary in this case. A comparison of the integrated transmittance and reflectance parameters is also made. Here clear similarities can be seen for high tilt angles where the incident light predominantly sees the white side of the slat. This is encouraging since the diffuse properties of the white side of the slat should be reasonably well approximated with a Lambertian fit.

This is a first step towards obtaining full BSDFs for complex window and shading systems. There is no doubt that more work is needed to develop further a procedure that will minimize the need for extensive

optical measurements without significantly compromising the results. Here, admittedly two extreme sets of fitting parameters are used and comparison of intermediate combinations of simplified fits and measured data are of interest.

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