INCLUDING OF SPECULAR COMPONENT IN A BTDF OR BRDF ASSESSMENT BASED ON DIGITAL IMAGING

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ABSTRACT

Bi-directional Transmission (or Reflection) Distribution Functions, commonly named BTDFs (and BRDFs), are essential quantities to describe any complex fenestration system in details. They are defined as the ratio of the luminance diffused from a surface element in a given direction (after transmission or reflection), and the illuminance incident on the sample. However, these functions are capable of describing the regular (specular) as well as the diffuse components of emerging light, and their mutual knowledge is necessary to assess a glazing or shading system's optical performances properly. Although the analytical expression of a BT(R)DF differs whether it is related to regular (specular) or diffuse light, a simultaneous assessment of the two components can be achieved under certain conditions, presented in this paper. They are thereafter analyzed for the particular data acquisition procedure developed for a novel type of bi-directional photogoniometer, based on digital imaging.

RÉSUMÉ

Les Fonctions de Distribution de Transmission (ou Réflexion) Bi-directionnelle, appelées BTDFs (et BRDFs), sont des grandeurs essentielles pour décrire avec prcision les proprits photomtriques d'un système de fenêtre complexe. Elles sont définies comme le rapport de la luminance diffusée depuis un élément de surface dans une direction (après transmission ou réflexion), et de l'éclairement incident sur l'échantillon. Cependant, ces fonctions sont également capables de caractriser la composante rgulire (spculaire) de la luminance, et la connaissance combinée de cette dernière avec la composante diffuse est nécessaire pour évaluer les performances optiques de systèmes de vitrage ou de protection solaire. Malgré des expressions analytiques différentes d'une BT(R)DF pour les composantes rgulire (spculaire) ou diffuse, une mesure simultanée des deux composantes peut être effectuée sous certaines conditions, présentées dans cet article. Elles sont ensuite analyses pour la méthode particulière d'acquisition de données développée pour un nouveau type de photogoniomètre bidirectionnel basé sur l'imagerie numérique.

INTRODUCTION

The detailed characterization of complex fenestration systems requires the determination of their Bi-directional Transmission (or Reflection) Distribution Function, named BTDF (or BRDF). This function is defined for scattered light as "the quotient of the luminance of a surface element in a given direction, by the illuminance incident on the sample" [1], and is expressed by equation (1). It is assessed with a specific measurement device, called photogoniometer. An important issue in its assessment is the separation of diffuse from regular (specular) emerging light, in order to meet the CIE specifications. More however is the fact that their expressions are different: as illustrated by Fig. 2(A), the specular part is not related to a solid angle, and varies with the distance from source to detector, whereas the diffuse part depends on the considered solid angle, and therefore appears as a function of the distance from sample to detector.

$$BT(R)DF(\theta_1, \phi_1, \theta_2, \phi_2) = \frac{L_2(\theta_1, \phi_1, \theta_2, \phi_2)}{E_1(\theta_1)} \tag{1}$$

where (θ_1, ϕ_1) are the polar coordinates of the incoming light flux, (θ_2, ϕ_2) and L_2(θ_1, ϕ_1, θ_2, ϕ_2) are respectively the polar coordinates and the luminance of the emerging element of light flux, and $E_1(\theta_1)$ is the illuminance of the sample, due to the incoming light flux.

However, as pointed out in [2], BT(R)DFs are capable of describing both regular (specular) and diffuse light components. In the first case, they will keep a finite value determined by the incident angle, the transmittance (reflectance), and the source solid angle, and only in the limit of a vanishingly small source solid angle will a regular (specular) BT(R)DF approach infinity. By expressing both types of BT(R)DFs and comparing their associated equations, one can find out what conditions would be necessary for them to be considered as equivalent, and therefore for accepting to assess experimentally both components together.

In this paper, these conditions are determined for the specific case of a novel digital imaging-based bi-directional photogoniometer [3]. Their impact on assessed BT(R)DF values is thereafter investigated for prismatic panels, representative of complex glazing with strongly specular transmission features.

BT(R)DF ASSESSMENT METHOD

The assessment method of the bi-directional photogoniometer considered in this paper differs from conventional ones in the way that it splits the emerging hemisphere into a regular grid of averaging zones of freely chosen angular dimensions ($\Delta\theta_2$, $\Delta\phi_2$), which therefore prevents from missing any discontinuity in the emerging luminance figure. The functioning principle, illustrated by Fig. 1, is the following: light emerging from the sample is reflected by a diffusing triangular panel towards a charge-coupled device (CCD) camera, used as a multiple points luminance-meter [3]. After six 60° rotations of the screen-camera system, the emerging light distribution is fully determined in a very short time (about a minute). For reflection measurements (Fig. 1B), some additional constraints appear due to the conflict of incident and emerging light flux: the incoming beam needs to penetrate the measurement space and reach exactly the sample surface, and requires a special opening through the screen when the latter is obstructive.

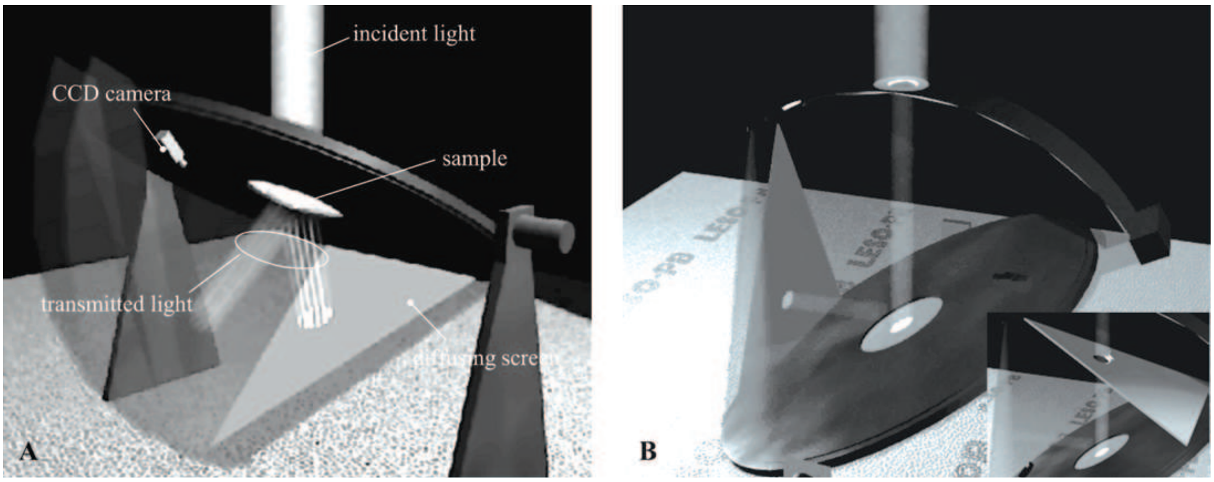

Figure 1: Functioning principles of bi-directional photogoniometer based on digital imaging techniques. (A) Detection of transmitted light flux. (B) Detection of reflected light flux.

The light source consists of a HMI 2.5 kW discharge lamp with a Fresnel lens, placed at 6.5 m from the sample (it has been changed since and moved to 9 m); it provides a very uniform illumination of the sample area A (1.8% relative mean deviation) and a beam collimation of about 0.4° half angle [3]. The illuminance measured perpendicularly to the incident beam has been checked to follow Bouguer's law ($E_1 \propto \frac{1}{\text{dist}^2}$) with 99% accuracy; the beam can therefore be considered as coming from a point source situated at a distance $h = \frac{1}{2}D \tan 0.4$, where D is the sample diameter, i.e. at about 7.2 m for D = 10 cm.

As the source area is in practice larger than the sample, any element of light flux received by a surface element dA on the sample will be emitted from a source surface element dA_{source} comprised in a solid angle from dA of 0.4° half angle. Hence, the probability that an element dA_{source} contributes to dA's illumination is inversely proportional to its distance to the source centre, maximal within the source disk of radius $\frac{1}{2}D - 6.5 \tan 0.4$ and null outside radius $\frac{1}{2}D + 6.5 \tan 0.4$, which leads to an average emitting disk A_{source} of radius $\frac{1}{2}D$.

REGULAR (SPECULAR) AND DIFFUSE COMPONENTS OF EMERGING LIGHT FLUX

As the incident illuminance $E_1(\theta_1)$ in equation (1) is independent of whether the emerging light is diffuse or regular (specular), we can compare the expressions of BT(R)DFs by analyzing those of the luminance emerging from the sample L_2 for both cases. For the device described here, it would actually be even preferable to compare the expressions of the luminance L_{screen} emitted by the projection screen and detected by the CCD camera, which is the quantity determinant in the BT(R)DF assessment, as schematised in Fig. 2(B).

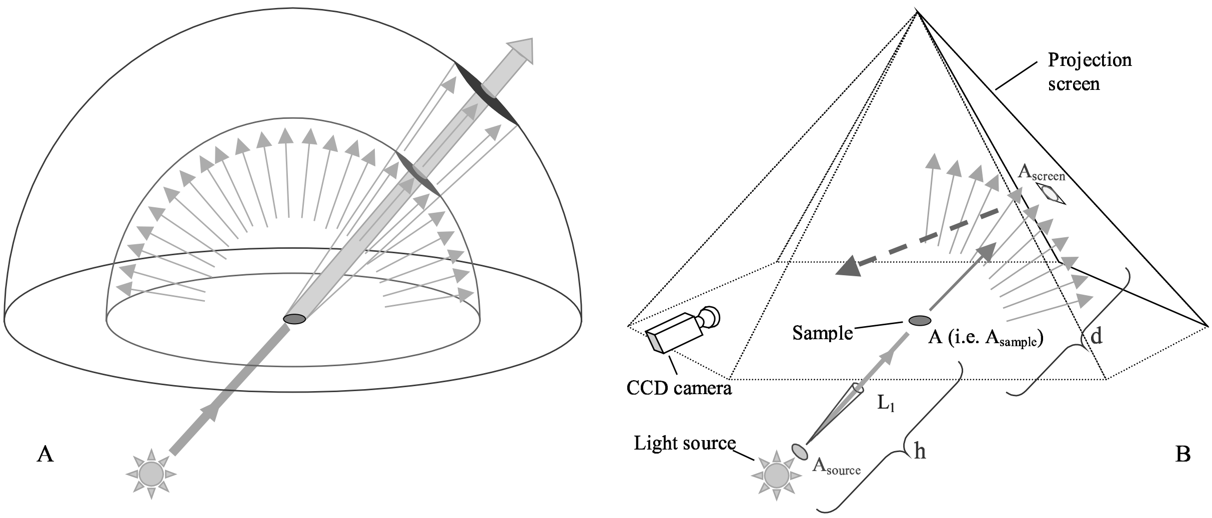

Figure 2: Detection of light transmitted through a sample (same principle for reflection). (A) Specular component against diffuse transmission. (B) Detection with screen and CCD camera.

Replacing the formal differential quantities by their equivalent average values [2], equations (2) respectively describe the luminance emitted from the screen due to regular (L_{screen_spec}) and diffuse (L_{screen_diff}) transmission, the latter being deduced from equation (1). Both definitions require the projection screen to be perfectly diffusing (lambertian), which, as shown in [3], is a very reasonable assumption.

$$L_{screen\_spec} = \tau_{\text{d/h}} \frac{\rho_{screen}}{\pi} \frac{h^2 \cos\alpha}{(h+d)^2 \cos\theta_1} E_1 \qquad L_{screen\_diff} = \frac{\rho_{screen}}{\pi} \frac{L_2 A \cos\theta_2 \cos\alpha}{d^2} \quad (2)$$

where $\tau_{\text{d/h}}$ is the directional-hemispherical light transmittance of the sample, ρ_{screen} is the hemispherical reflection factor of the projection screen, d is the distance from sample centre to screen along direction (θ_2, ϕ_2) and α is the angle between the latter and the normal to the screen; the same development is valid throughout equation (8) for reflection, replacing $\tau_{\text{d/h}}$ with $\rho_{\text{d/h}}$.

If the regular and diffuse components of the emerging light are not separated during the measurement phase, inducing that quantities L_{screen_spec} and L_{screen_diff} are converted likewise into BT(R)DF data, expressions (2) must be equivalent under the actual experimental conditions. This condition is analyzed in the following section.

CONDITIONS FOR A SIMULTANEOUS ASSESSMENT OF SPECULAR AND DIFFUSE LIGHT

Considering equations (2) to be equivalent leads to relation (3) to be verified:

$$L_2 \approx \tau_{\text{d/h}} \frac{d^2 h^2}{(h+d)^2} \frac{1}{A \cos\theta_1 \cos\theta_2} E_1 \tag{3}$$

Replacing E_1 by its definition as a function of luminance for a point source (i.e. by $L_1 \cos\theta_1 \Omega_1$, where L_1 is the luminance of the incoming light flux and Ω_1 its associated solid angle $\frac{A_{source}}{h^2}$), we obtain relation (4):

$$L_2 \approx \tau_{\text{d/h}} \frac{d^2}{(h+d)^2} \frac{A_{source}}{A \cos\theta_2} L_1 \tag{4}$$

Expressing L_1, L_2 and $\tau_{\text{d/h}}$ by their formal definitions (still in average quantities), given by equations (5), where Φ_i is the incident (i=1) and emerging (i=2) light flux andΩ_2 the solid angle determined by outgoing direction (θ_2, ϕ_2), area A_{screen} being defined by ($\Delta\theta_2$, $\Delta\phi_2$):

$$\begin{aligned} L_1 &= \frac{\Phi_1}{A_{source}\Omega_1 \cos\theta_1} \\ L_2 &= \frac{\Phi_2}{A\Omega_2 \cos\theta_2} \\ \tau_{\text{d/h}} &= \frac{\Phi_2}{\Phi_1} \end{aligned} \tag{5}$$

we can rewrite relation (4) into (6):

$$\frac{1}{\Omega_2} \approx \frac{d^2}{(h+d)^2} \frac{1}{\Omega_1 \cos\theta_1} \tag{6}$$

As A and A_{source} are considered equal (see above) and according to the solid angle definition for Ω_1 and Ω_2, we can write equations (7):

$$\begin{aligned} \Omega_1 &= \frac{A}{h^2} \\ \Omega_2 &= \frac{A_{screen} \cos\alpha}{d^2} \end{aligned} \tag{7}$$

This finally leads to the conditions that have to be fulfilled by the digital imaging-based photogoniometer for assessing both regular (specular) and diffuse light components, which are expressed by relation (8): the ratio of squared distances from sample to source and from detector to source must be as close as possible to the ratio of the apparent surfaces of the sample and the averaging (discretization) zone, apparent in the sense of being seen respectively along the incident and emerging directions.

$$\frac{h^2}{(h+d)^2} \approx \frac{A \cos\theta_1}{A_{screen} \cos\alpha} \tag{8}$$

IMPACT ON BT(R)DF ASSESSMENT ACCURACY

In order to evaluate how strongly the fulfillment of relation (8) influences the BT(R)DF results provided by the experimental facility presented above, a simulation model of the latter was constructed with the commercial ray-tracing software TRACEPRO®[1]. Measured BTDFs for prismatic glazing were compared first to simulated values obtained with a faithful copy of the experimental device, then to new simulation results, achieved with an ideal set-up model [4].

This ideal set-up consists of a virtual sun as the light source, presenting a beam spectrum and spread (0.25°) as close as possible to the real sun, and a hemispherical detector, perfectly absorbing to avoid inter-reflections, and of optimized diameter to satisfy relation (8): as the light source is considered infinitely far away, the ratio $h^2/(h+d)^2$ tends to 1, and therefore, the ratio $(A\cos\theta_1)/(A_{screen}\cos\alpha)$ (or rather $A\cos\theta_1/A_{screen}$ as the averaging areas A_{screen} are normal to the rays for a hemispherical detector) needs to be as close to 1 as possible. Both the sample area A and the averaging grid resolution ($\Delta\theta_2$, $\Delta\phi_2$) being fixed by the experimental conditions, the values of A_{screen} over the hemisphere will be determined only by the virtual detector's radius. The latter is therefore calculated in order that the average value of the right-hand part of equation (8) equals 1 over the default set of 145 incident directions (θ_1, ϕ_1) (or more specifically over the set of values for θ_1 weighted by each one's occurence in the default incident directions set).

By observing the discrepancies between BTDF values obtained for optimal conditions (ideal set-up model) and measured data or simulated values under real conditions, one can find out how the fulfillment of equation (8) influences the the results accuracy, and to what extent an approximation is acceptable, as the relation will of course not be perfectly verified in practice. As a matter of fact, as h is equal to 7.2 m and the average distance d from sample to diffusing screen is 0.905 m; we thus obtain a distance ratio of 0.79, whereas the average value of the area ratio is 1.01 [4].

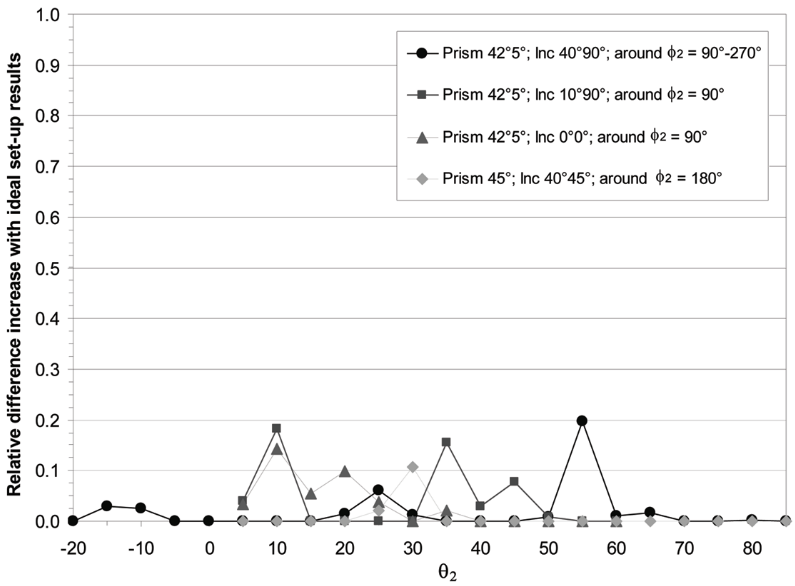

Figure 3: Relative increase of discrepancies for BTDFs calculated with the ideal model compared to measured and simulated data under real conditions.

[1] TRACEPRO®, v. 2.3 & 2.4, Lambda Research Corporation.

However, as observed on Fig. 3, the impact of condition (8) on the BTDF values is by far lower than 22%: more than 9 out of 10 remain inferior to 10%. This shows that although equation (8) is only approximately fulfilled for the present photogoniometer set-up, BTDF results (and likewise BRDFs) remain coherent and reliable even for the strongly regular (specular) light distributions observed with prismatic panels. One can therefore reasonably admit a simultaneous measurement of light emerging in diffuse and regular (specular) ways for this particular digital imaging-based assessment device.

CONCLUSION

The separation of the diffuse component of emerging light flux from its regular (specular) features is a critical issue in characterizing the bi-directional optical properties of a fenestration system in transmission (or reflection), because the two components differ in their analytical definition. However, when the BT(R)DF assessment method relies on the splitting of the emerging hemisphere into a grid of adjacent angular zones inside which BT(R)DF values are averaged, the simultaneous assessment of both components can be accepted under specific geometric conditions, that are presented in this paper. They determine a compromise to find between the distances from the sample to the source or the detector, and the apparent areas of the sample and the averaging zones.

In order to estimate how strongly these geometric conditions influence the accuracy of BT(R)DF results achieved with a digital imaging-based photogoniometer, two ray-tracing simulation models of the latter were constructed: one as faithful as possible and the other based on optimal components and geometry that fulfilled the conditions perfectly. The comparison of BT(R)DF results showed that the assumptions made for the building up of the instrument were reasonable, the assessment method allowing as a consequence to measure diffuse and regular (specular) components together, which suggests to revisit in the future the formal CIE definition of the corresponding photometric figure.

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