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Lighting simulation for External Venetian blinds based on BTDF and HDR sky luminance monitoring

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ABSTRACT

The precise daylighting simulation in buildings can potentially contribute to designers' and occupants' smart utilization of it. The traditional method of employing sky models was indicated with noticeable errors in transient lighting simulation for complex fenestration systems (CFS), due to the mismatch between the real sky and standard sky models. This paper evaluates the performance of a calibrated embedded photometric device based on sky luminance monitoring, capable of real-time on-board lighting computing. Daylighting experiments for external Venetian blinds (EVB) were conducted in a lighting test module to demonstrate its accuracy in the simulation of horizontal work-plane illuminance. The BTDF of the EVB was generated for two different tilt angles of slats respectively. With partly cloudy skies, the photometric device was validated with improved accuracy in simulating the work-plane illuminance distribution compared with a common practice employing the Perez all-weather sky model.

KEYWORDS

BTDF, HDR, Workplane illuminance, Venetian blinds, Transient Simulation

INTRODUCTION

Lighting constitutes about 15 - 30% energy consumption in non-residential buildings (ul Haq et al., 2014). The utilization of daylight, as a free source, can potentially mitigate the energy consumption of buildings at a considerable scale and, at the same time, contributes to occupants' health condition and working performance (Mills et al., 2007). However, excessive penetration of daylight into buildings can increase the cooling load and glare probability for occupants. To overcome this issue, shading devices or electrochromic glazing is commonly applied in commercial and residential buildings for the regulation of daylight provision and the prevention of glare. Despite of their merits in tuning daylighting, the complexity of their architecture, with curved profile or micro structures, makes it difficult for designers to pre-plan the room or to dynamically control the daylight precisely.

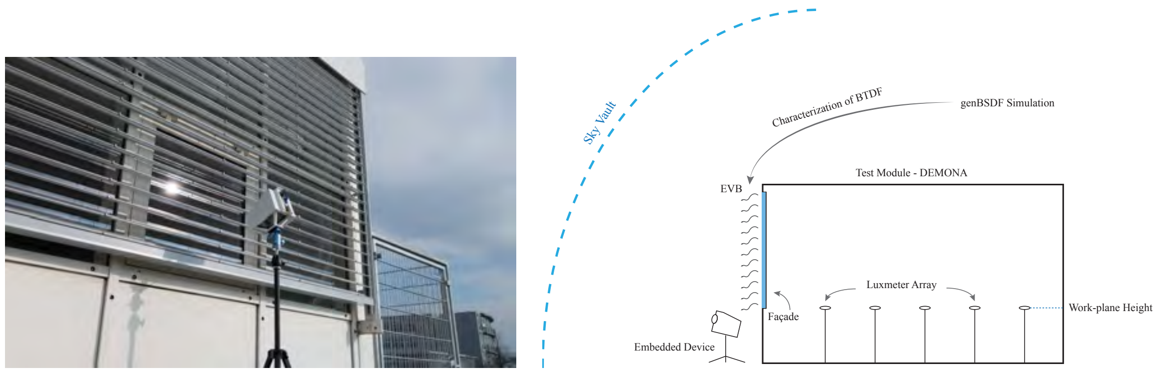
The bi-directional transmittance distribution function (BTDF) describes the light transmittance behaviour of a certain material or a complex fenestration system (CFS). The function is defined by the ratio of directional exiting radiance over the incident irradiance on a surface (Dereniak et al., 1982). The BTDF is a five-dimensional quantity, with two sets of spherical coordinates for incident and exiting directions respectively as well as the wavelength of light. In the context of photometric scope, the variable of wavelength can be cancelled by the integration with the luminosity function $V(\lambda)$ over the wavelength. Over the past decades, multiple angular basis has been defined, which discretize the BTDF with a finite number of incident and exiting directions, including the Tregenza and Klems basis (Tregenza, 1987; Klems and Warner, 1995). Together with the ray-tracing techniques, the BTDF of a CFS can be used to calculate the daylight provisions and assess glare risks in buildings, however, the BTDF of a CFS is limited by a number of factors in daylighting application: firstly, the approximated BTDF commonly neglects the spatial variation over different positions on the incident surface plane, which takes the average over a periodic section; secondly, although the BTDF can be either generated by using simulation software, with the defined surface properties and geometry, or monitored by a Gonio-photometer, the cost and time can be considerable for a CFS with multiple states; last but not the least, the resolution of the BTDF has to balance between the computation load and accuracy in lighting simulation.

For dynamic regulation of daylighting, the accuracy of transient lighting simulation is constrained by the mismatch between the standard sky models and the real sky. The standard sky models can hardly reproduce the real sky for a specific location and moment, because they are based on averages over a range of sky types, including the CIE standard sky model and Perez all-weather sky model (Perez et al., 1993). In addition, a limited number of input weather data is not sufficient to reconstruct the reality, since the sampling frequency of inputs were not over two times the maximum spatial frequency of the sky, according to the Shannon sampling theory (Shannon, 1949). Especially for partly cloudy skies with scattered high contrast sky patches, the discrepancy between the standard sky models, with smooth luminance distribution, and the reality can be pronounced, contributing to substantial error in transient lighting simulation from the simplified source of daylighting.

In this paper, an embedded photometric device (Wu et al., 2017b,a), integrating the sky luminance monitoring and on-board lighting computing, is validated experimentally in the horizontal work-plane illuminance simulation for external Venetian blinds (EVB) in a daylighting testbed. The device, employing high dynamic range (HDR) imaging techniques, is able to monitor the luminance of the sun orb, the sky and landscape during the day with high resolution mapping, which can potentially reproduce the real sky more accurately than the standard sky models. The BTDF was generated for the EVB at various tilt angles and employed in the daylighting simulation.

METHODOLOGY AND EXPERIMENTS

One EVB, with a sinusoidal profile, was installed in a lighting test module, as illustrated in Figure 1 a). The profile of the EVB was modelled with the identical geometry in RADIANCE (Larson and Shakespeare, 2004), an open source lighting simulation software employing ray-tracing techniques. To improve the accuracy in lighting simulation, the reflectance of the surface material of the EVB at both sides were measured by a chromameter (MINOLTA CR-220) and its specularity was monitored by a gloss meter (MINOLTA GM-060), characterizing the specular component at 60° incident angle to approximate the specularity. As various tilt angles of its slats correspond to different light transmittance properties, a group of BTDF for the EVB was computed by the 'genBSDF', a sub-program of RADIANCE, at 5° interval of tilt angles respectively. In the scope of this paper, two tilt angles were evaluated at 72° and 32° respectively to the vertical plane, directing downward. Their BTDF was generated employing the Klems angular basis, with 145 incident and exiting directions respectively. During the lighting simulation, the EVB was defined as the 'BSDF material' with proxy geometry in the RADIANCE. In this way, the direct tracing rays interact with the modelled geometry of the EVB, while the indirect rays, with multi-reflections, use the BTDF to compute lighting, reducing the computation load for ambient calculation.



(a) The device positioned in front of the EVB

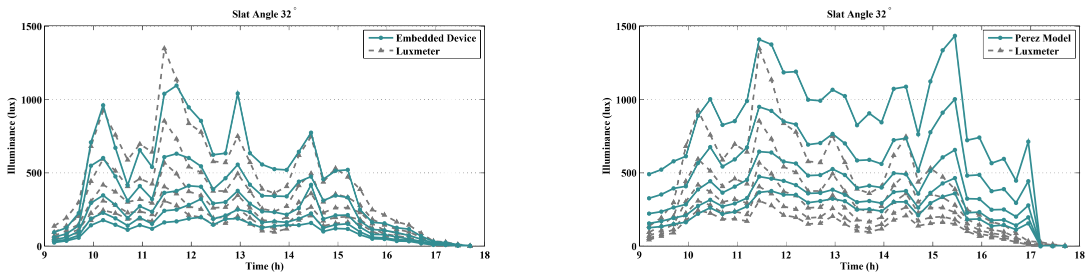
(b) Schematic of the set-up

Fig. 1. The experimental set-up for testing the embedded photometric device

To validate the daylighting simulation of the embedded photometric device, 'in situ' experiments were conducted in a retrofitted test module (interior size: $6.4 \times 2.9 \times 2.6$ m^3), equipped with a unilateral façade reaching a 0.62 window-to-wall ratio and with the EVB. This module was modelled at 1:1 scale with surface material properties monitored by the chromameter and gloss meter, including the wall, ceiling, floor, and surfaces of each furniture. The photometric device was positioned in front of the EVB with its lens targeting toward the sky vault, as shown in Figure 1 a). The modelled scene was embedded into the device with its on-board RADIANCE software operating for quasi real-time lighting simulation. The embedded photometric device, as a compact platform, calculated the horizontal work-plane illuminance distribution at 1 m, 2 m, 3 m, 3.9 m, and 4.7 m distance to the façade. To assess its accuracy, an array of lux-meters was positioned at identical positions inside the module to monitor the work-plane illuminance as reference, illustrated in Figure 1 b). Each lux-meter was connected to a data logger, recording the illuminance simultaneously. For comparison, both the embedded device and lux-meters were synchronized to simulate and monitor the work-plane illuminance respectively every 15 min. Furthermore, the direct normal and diffuse horizontal irradiance were monitored by a pyranometer at the rooftop for contrasting the performance employing the Perez all-weather sky model.

RESULTS

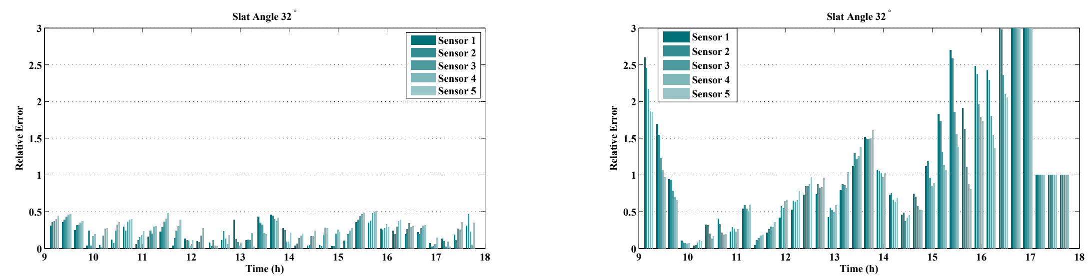
For a partly cloudy day, the slats of the EVB were fully stretched and directed downward at 32° to the vertical plane. The horizontal work-plane illuminance simulated by the embedded photometric device from 9:00 to 18:00, based on HDR imaging techniques, is illustrated in Figure 2 a), with green data points and curves. The five curves stacked from up to bottom represent the five sensors at different distance to the façade respectively. The monitored illuminance values by using the lux-meters are denoted by grey dotted lines stacked similarly as reference. In comparison, the illuminance simulated by using the Perez all-weather model was illustrated in Figure 2 b) by stacked green lines. According to the two figures, the simulated illuminance by using the embedded device is closer to the monitored value than that employing the Perez all-weather sky model. The relative error, as shown in Figure 3, further illustrates the merits of the HDR imaging techniques in reconstructing the sky. The Perez sky model is not well performing in simulating relatively dim skies and tend to have pronounced error, when the sky has scattered high contrast patches. The average relative error for work-plane illuminance by the embedded device at the five positions is 18.7%, 19.1%, 22.7%, 24.7%, and 27.2% respectively, while that by employing the Perez all-weather model is 169.1%, 166.0%, 144.1%, 133.4%, and 134.1% respectively.



(a) Embedded device

(b) Perez all-weather model

Fig. 2. Simulated horizontal work-plane illuminance by using the two approaches to reproduce the sky (32° tilt angle)

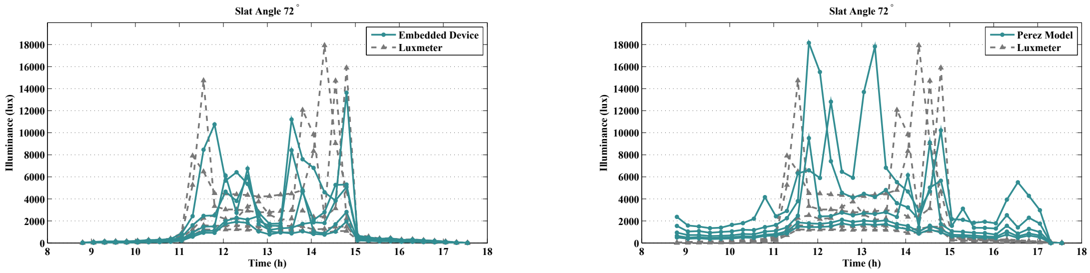


(a) Embedded device

(b) Perez all-weather model

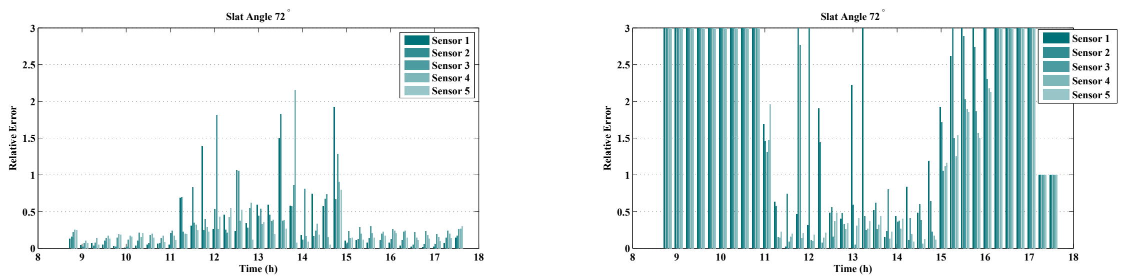
Fig. 3. Relative error in the simulated horizontal work-plane illuminance by using the two approaches (32° tilt angle)

For the tilt angle of slats at 72° to the vertical plane, the simulated work-plane illuminance and its relative error are illustrated in Figure 4 and Figure 5 respectively. The embedded photometric device out-performs the Perez sky model in transient simulation, especially for relatively dim skies with thick clouds and with high contrast sky patches. The spikes of error bars at mid-day were possibly due to the exposure of the lux-meters to the sun disk through the spacing of the EVB slats. For clear illustration and comparison, the error bar is not scaled to include the maximum peaks. The average relative error at the five positions through out the day for the embedded device is 35.8%,33.8%, 42.1%, 34.9% , and 24.8%, while that for the common practice employing Perez all-weather model is 659.6%, 538.7%, 401.2%, 378.9%, and 400.0%.



(a) Embedded device (b) Perez all-weather model

Fig. 4. Simulated horizontal work-plane illuminance by using the two approaches to reproduce the sky (72° tilt angle)



(a) Embedded device (b) Perez all-weather model

Fig. 5. Relative error in the simulated horizontal work-plane illuminance by using the two approaches (72° tilt angle)

CONCLUSIONS

Daylighting simulation is contingent on the mismatch between the modelled sky and real sky particularly for transient analysis. This paper demonstrates an embedded photometric device, integrating the HDR sky luminance monitoring and on-board lighting computing, in the daylighting simulation of horizontal work-plane illuminance for an EVB with a sinusoidal profile. Experiments were conducted for the EVB in a lighting test module. The BTDF of the EVB at tilt angle 32° and 72° was generated by the genBSDF program respectively. Employing the BTDF and geometry of EVB in the daylighting simulation, the experimental results show the embedded photometric device, based on HDR sky luminance monitoring, improves the accuracy in simulating the transient work-plane illuminance than the common practice employing the Perez all-weather sky model, especially for partly cloudy skies with high contrast sky patches. Despite of its merits in annual lighting analysis, the Perez model may have pronounced mismatch with the real sky for a specific location and moment.

Although the embedded photometric device, based on HDR sky luminance mapping, reproduces the sky more accurately than sky models, its computation load and bulky input data can limit its application in annual daylighting analysis, including daylight autonomy. The device is advantageous in applications sensitive to the accuracy of daylighting simulation, including dynamic shading control and building retrofitting. Its accuracy can be potentially improved further by the BTDF with higher resolution, which will be studied in the future.

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