Measurement of bidirectional reflection distribution function on material surface

Wei Zhang (张 伟), Hongyuan Wang (汪洪源)*, and Zhile Wang (王治乐)

Research Center for Space Optical Engineering, Harbin Institute of Technology, Harbin 150001

**E-mail: fountainhy@163.com*

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Two automatic measurement methods of bidirectional reflection distribution function (BRDF) are presented based on absolute and relative definition. Measurement principle and scheme of the methods are analyzed. A real-time measurement device is developed, the measurement spectral range of which is from ultraviolet to near infrared with 2.4-nm wavelength resolution, and the angular range is $0° - 360°$ in azimuth angle and $0° - 85°$ in zenith angle with $0.01°$ angle resolution. Absolute measurements of BRDF on tinfoil and ceramic tile are performed and the test materials present apparent specular reflection characteristics. The theoretical error in the experiment is about 6.05%. The BRDF measurement results are closely related to the precision of measurement platform, the sensitivity of measurement instrument, and the stability of illuminating light source.

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With the development of computer technology, the research on target properties has been widely developed[1−3]. Bidirectional reflection distribution function (BRDF) is gradually introduced to measure and model the object characteristics. For instance, BRDF is used to study the material quality and the light reflection properties of object surface by means of mathematical and physical model, which provides an efficient facility for target detection and recognition. So it is very important to make researches on measurement method of BRDF[4−6].

The BRDF $f(\theta_\mathrm{i}, \varphi_\mathrm{i}; \theta_\mathrm{r}, \varphi_\mathrm{r}, \lambda)$ is an expression of the physical property of a material, which describes the pattern of light reflected from a surface of the material to all directions above the surface, for all directions of incident light. It is a five-dimensional function about incident zenith angle θ_i, reflected zenith angle θ_r, incident azimuth angle φ_i, reflected azimuth angle φ_r, and wavelength λ. For a material surface and a certain wavelength, BRDF determines the appearance of materials for different viewing directions, which is defined as the ratio of the radiance $\mathrm{d}L_\mathrm{r}(\theta_\mathrm{r}, \varphi_\mathrm{r})$ reflected from a surface in the direction $(\theta_\mathrm{r}, \varphi_\mathrm{r})$ to the incident irradiance $\mathrm{d}E_\mathrm{i}(\theta_\mathrm{i}, \varphi_\mathrm{i})$ onto the surface from the direction $(\theta_\mathrm{i}, \varphi_\mathrm{i})$ (see Fig. 1):

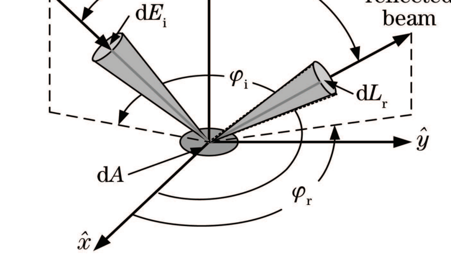

Fig. 1. Light reflection geometry.

$$f(\theta_\mathrm{i}, \varphi_\mathrm{i}; \theta_\mathrm{r}, \varphi_\mathrm{r}) = \frac{\mathrm{d}L_\mathrm{r}(\theta_\mathrm{r}, \varphi_\mathrm{r})}{\mathrm{d}E_\mathrm{i}(\theta_\mathrm{i}, \varphi_\mathrm{i})}, \quad (1)$$

where the radiance $\mathrm{d}L_\mathrm{r}(\theta_\mathrm{r}, \varphi_\mathrm{r})$ is the radiant power flow per unit solid angle and unit area normal to the reflected rays and holds the unit $\mathrm{W/(m^2 \cdot sr)}$, the irradiance $\mathrm{d}E_\mathrm{i}(\theta_\mathrm{i}, \varphi_\mathrm{i})$ is the power flux density irradiating a surface per unit area and holds the unit $\mathrm{W/m^2}$.

According to the BRDF definition, absolute measurement method of BRDF is to measure the incident spectral irradiance and the reflected spectral radiance by using illuminance meter and luminance meter respectively.

The beam from the light source passes through monochromator and collimator, and illuminates the sample surface in some incident angle. The incoming irradiance E_e on the sample surface can be achieved in terms of incident power of light source P_i and illuminated area A of the sample. The received radiance L_e on the detector can be calculated in terms of received power P_s, detecting solid angle Ω, and received area $A\cos\theta_s$[7]. Then the BRDF of test sample surface can be obtained according to the ratio of L_e and E_e, namely,

$$\mathrm{BRDF} = \frac{L_e}{E_e} = \frac{(P_s/\Omega A\cos\theta_s)}{(P_\mathrm{i}/A)} = \frac{P_s}{P_\mathrm{i}\Omega\cos\theta_s}(\mathrm{sr}^{-1}). \quad (2)$$

Relative method of BRDF measurement is implemented by comparing the test sample with a reference sample whose surface property is known. Relative measurement of BRDF needs to select a Lambertian surface as the standard reference sample[8].

Since the reflection characteristics of object surface change slightly in azimuth direction, and the incident and outgoing paths of light beam are about identical for the test and reference samples on the same variable-angle testing device, the specific expression of relative measurement of BRDF can be shown as

$$\mathrm{BRDF}(\theta_\mathrm{i}, \varphi_\mathrm{i}; \theta_\mathrm{r}, \varphi_\mathrm{r}) = f_\mathrm{r}\frac{V_s}{V_\mathrm{ref}}\frac{\cos\theta_\mathrm{ref}}{\cos\theta_s}, \quad (3)$$

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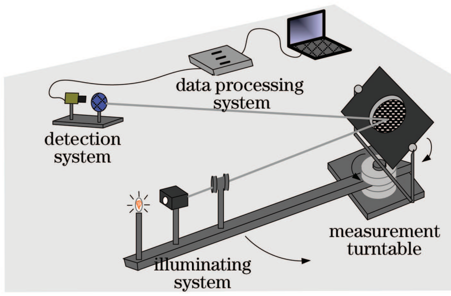

Fig. 2. Schematic design of BRDF absolute measurement.

where f_r is the BRDF of the reference sample; V_s and V_{ref} are the output voltages on the detector for test sample and reference sample; θ_s and θ_{ref} are the reflected zenith angles of the test and reference samples.

The schematic design of BRDF absolute measurement is shown in Fig. 2. The measurement equipment consists of four parts: a broadband light source, a positioning mechanism with three motor-controlled axes of rotation, a high sensitivity spectroradiometer detector, and a computer system to control the operation, data acquisition, and data processing[9].

The test sample is mounted on a sample elevating table and the table can provide up and down movement for height calibration. The light source and the detector move along arc holders to achieve different incident zenith angle θ_i and reflected zenith angle θ_r, and the holders with slidewheels driven by stepping motor circle along the slideway of measurement platform to get different incident azimuth angle φ_i and reflected azimuth angle φ_r[10]. The scheme of BRDF relative measurement is shown in Fig. 3.

Then a BRDF test experiment can be implemented after related equipments, such as light source, detector, scale range etc., are calibrated for providing required measurement accuracy.

The measurement devices include illuminating system, detection system, measurement turntable, and control system according to the schematic design of absolute and relative BRDF measurements[11]. The light source used to illuminate the sample is Avalight-DH-S, a combined deuterium and halogen light source made in Holland, which can be used for ultraviolet/visible/near-infrared (UV/VIS/NIR) applications. The light source supplies a continuous spectrum with high efficiency and stability in the wavelength range from 190 to 2000 nm. The detection system used in the experiment is AvaSpec-2048 spectrometer made by Avantes Corporation of Holland. It is a fiber optic spectrometer based on the AvaBench-75 symmetrical Czerny-Turner design with 2048-pixel charge-coupled device (CCD) detector array. The spectrometer consists of fiber optic entrance connector, collimating and focusing mirror, and diffraction grating. The motorized precision rotary stages made in Beijing Optical Instrument Factory are adopted to build the measurement turntable. The turntable consists of a MRS101 rotary stage (mesa diameter Φ50 mm), two MRS103 rotary stages (mesa diameter Φ200 mm) rotary stages, a detector holder and cantilever, and a test sample bench. The control system is achieved by an SC113 step motor controller made in Beijing Optical Instrument Factory. The controller is equipped with a standard communication interface to combine the computer and the precision rotary stages, which provides a software basis for automatic measurement of BRDF. The technical data of the measurement devices are shown in Table 1.

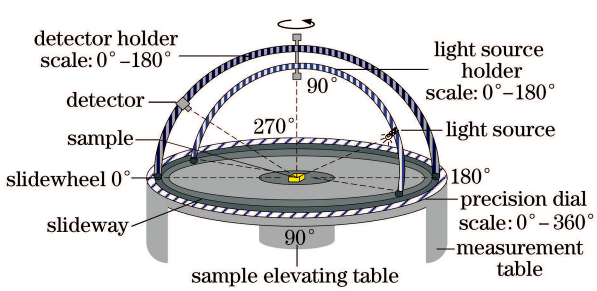

Fig. 3. Schematic design of BRDF relative measurement.

Table 1. Technical Data of the Measurement Devices

Parameter	Specification
Wavelength Range	200 − 1100 nm
Turntable Material	Stainless Steel/Pitch-Black
Coarse/Fine Adjustment	180°/2°
Angle Resolution	0.01°
Spectral Resolution	2.4 nm
Radial Swing	40 μarc
Displacement Precision	0.01 mm
Stability	0.1%
Stray Light	< 0.1%

In our experiment, the concrete measurement steps are as follows.

Step 1: Calibrating the illumination light source using Avalight-DH-CAL.

Step 2: Calibrating the spectrometer by adjusting the dynamic range and integral time.

Step 3: Positioning the fiber-optic probe of light source on the holder and adjusting the height of the probe to align the center of the test sample.

Step 4: Positioning the fiber-optic probe of the spectrometer on the holder and seting the distance of the probe to the sample center to avoid overflow.

Step 5: Operating the step motor controller to measure BRDF.

In this way, the BRDF measurement results for different incident and reflected angles can be achieved.

Absolute measurements of BRDF on yellow tinfoil, black and glossy ceramic tile are made for the incident angles of 30°, 45°, 60°, respectively. The relation curves of BRDF, wavelength, and reflected angle are obtained, as shown in Figs. 4 and 5. From the experimental results, it can be concluded that the test materials present apparent specular reflection characteristics.

There are several factors that may introduce error in the experiment. The error ε_{BRDF} can be expressed as

$$\varepsilon_{BRDF}^2 = \varepsilon_{ME}^2 + \varepsilon_{IE}^2 + \varepsilon_{DE}^2 + \varepsilon_{PE}^2, \tag{4}$$

where ε_{ME} is the mechanical system error, ε_{IE} is the illuminating system error, ε_{DE} is the detection system error,

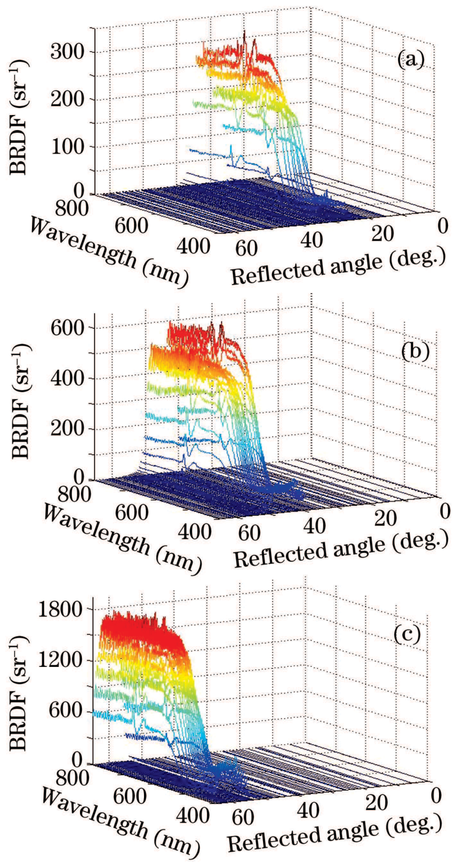

Fig. 4. Relation of BRDF, wavelength, and reflected angle on tinfoil material surface for incident angles of (a) 30°, (b) 45°, and (c) 60°.

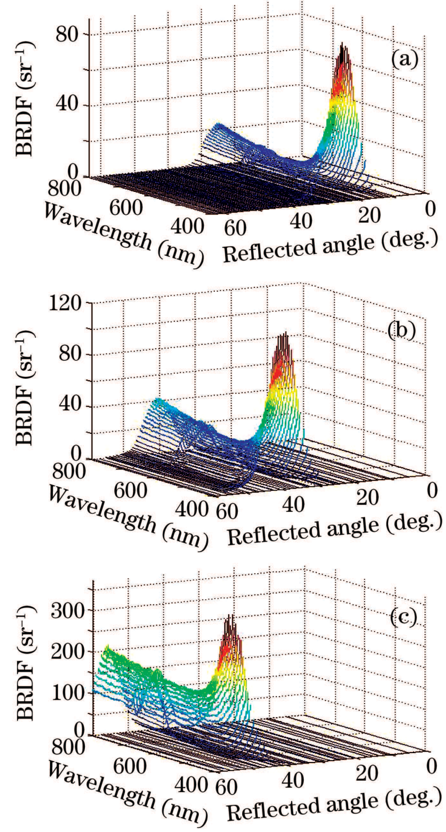

Fig. 5. Relation of BRDF, wavelength, and reflected angle on ceramic tile surface for incident angles of (a) 30°, (b) 45°, and (c) 60°.

$\varepsilon_{\rm PE}$ is the personal error.

The mechanical system error $\varepsilon_{\rm ME}$ is

$$\varepsilon_{\rm ME}^2 = \varepsilon_{\rm re}^2 + \varepsilon_{\rm he}^2 + \varepsilon_{\rm de}^2, \qquad (5)$$

where $\varepsilon_{\rm re}$ is the rotation error of the motorized precision rotary stages and its absolute value is less than 0.0003° for MRS101 and 0.0002° for MRS103; $\varepsilon_{\rm he}$ is the height error of the holder for the light source and detector and its absolute value is 0.03 mm; $\varepsilon_{\rm de}$ is the displacement error of the detector, namely the mechanical processing error of the detector cantilever, and its absolute value is 0.01 mm. Totally, the mechanical system error $\varepsilon_{\rm ME}$ is less than 3.34%.

The illuminating system error $\varepsilon_{\rm IE}$ is

$$\varepsilon_{\rm IE}^2 = \varepsilon_{\rm il}^2 + \varepsilon_{\rm rl}^2 + \varepsilon_{\rm sl}^2, \qquad (6)$$

where $\varepsilon_{\rm il}$ is the error from the stability of the illuminating light source since the incident light intensity may change over time due to the electric voltage change on the bulb, and it is 0.1%; $\varepsilon_{\rm rl}$ is the error from the time-variation of the reflected luminance, namely, the fact that the reflected luminances from different points of view are not detected at the same time will bring out error, and it is 0.4%; $\varepsilon_{\rm sl}$ is the error from stray light and it is controlled within 1% during the experimental process. Taking all the above factors into account, the illuminating system error $\varepsilon_{\rm IE}$ is less than 1.08%.

The detection system error $\varepsilon_{\rm DE}$ is

$$\varepsilon_{\rm DE}^2 = \varepsilon_{\rm snr}^2 + \varepsilon_{\rm nl}^2 + \varepsilon_{\rm sld}^2, \qquad (7)$$

where $\varepsilon_{\rm snr}$ is the error due to the signal-to-noise ratio, which is 0.004 for both incident power measurement and reflected power measurement; $\varepsilon_{\rm nl}$ is the error due to the nonlinearity of the detector, the error comes from detector array noise, null shift, and the low-frequency current noise of transistor in the preamplifier, and it is about 0.4%; $\varepsilon_{\rm sld}$ is the receiver solid angle error and the error stems from the z-direction misalignment and the receiver's aperture. The actual measurement shows that the z-direction misalignment error is 0.2 mm and the error from the aperture is 0.15%, and then the receiver solid angle error is 0.7%. So the detection system error is less than 0.9%.

The personal error $\varepsilon_{\rm PE}$ is caused by different readers. According to the actual measurement of several samples, $\varepsilon_{\rm PE}$ is 4.84%.

According to our experimental conditions, the overall error is

$$\varepsilon_{\rm BRDF} = \sqrt{\varepsilon_{\rm ME}^2 + \varepsilon_{\rm IE}^2 + \varepsilon_{\rm DE}^2 + \varepsilon_{\rm PE}^2} \approx 6.05\%. \qquad (8)$$

This is only the error analysis for ideal measurements. The actual BRDF measurement error is within 8.26% for yellow tinfoil material and within 7.88% for ceramic tile material due to some unpredictable reasons.

In conclusion, two automatic three-axis measurement systems designed to meet the needs of BRDF absolute and relative measurements are presented. The measurement equipment can cover almost the entire angular domain of an isotropic or anisotropic BRDF, and the angular range covers the entire incident and reflected hemispheres to an angle of at least 85°, with the exception of a cone of approximately 6° around retro-reflection. It can perform the real-time measurement of BRDF and the spectral range can cover almost the entire spectrum from UV to NIR with ample wavelength resolution.

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