Journal of Quantitative Spectroscopy & Radiative Transfer 131 (2013) 130–137

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

Quasi-specular reflection from particulate media

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ARTICLE INFO

Article history:
Received 30 November 2012
Received in revised form
28 February 2013
Accepted 5 March 2013
Available online 1 April 2013

Keywords:
Specular reflection
Gloss
Glint
Light scattering
Particulate media

ABSTRACT

Specular reflection is known to play an important role in many fields of scattering applications, e.g., in remote sensing, computer graphics, optimization of visual appearance of industrial products. Usually it can be assumed that the object has a solid surface and that the properties of the surface will dictate the behavior of the specular component. In this study I will show that media consisting of wavelength-sized particles can also have a quasi-specular reflection in cases where there are ordered structure in the media. I will also show that the quasi-specular reflection in particulate media is more than just a surface effect, and planar particle arrangement below the very surface can give rise to quasi-specular reflection. This study shows that the quasi-specular reflection may contribute in some cases in the backscattering direction, together with coherent backscattering and shadow-hiding effects.

1. Introduction

Specular reflection is one of the first topics taught in optics. In an idealized case of perfectly flat solid interface between two materials the geometrical optics approach is that one part of the incident light (or other wavelengths) is reflected into the specular direction and the rest is refracted into the second material. The amount of reflected and refracted power is given by the Fresnel coefficients. The approach that is often used to describe scattering from surfaces that are not ideally flat is that there is a diffuse component and a specular component in the scattered signal. This approximation is based on the microfacet idea [1,2] where it is assumed that the surface constitutes small planar facets. The facets are thought to be small, but still significantly larger than the wavelength so that their scattering can be modeled by specular reflection to the direction that is governed by the local normal vector of the facet. The specular reflection from surface consisting of microfacets is the sum of the first-order specular reflections from suitable facets, i.e., from facets where the local normal is such that the incidence angle, observation angle and the local normal will form a specular geometry. The more rough the surface is, the more the local normals are deviated from the average normal, and the more the specular signal is decreased and spread around the average specular direction. The diffuse scattering from microfacets comes from the multiple-scattered signals, but this alone cannot explain well the diffuse part so we will need some subsurface scattering assumption to explain the total diffuse part.

The specular reflection is modeled and measured in various fields. In remote sensing it is often called a 'glint' [3] and is observed when measuring scattering from oceans, ice covered areas and cirrus clouds, for example. In astronomy it seems that the radar reflectance properties of some Solar system targets, at least the Saturn moon Titan, need to be explained with a specular component [4,5]. In computer graphics reflectance models that will produce specularity are needed to create realistic images. With industrial materials and applications the specular part is usually called 'gloss', and can be either preferred or unpreferred feature in the visual appearance of the product. Certain cosmetic products, paints and papers seek to have high gloss.

In many cases the 'surface approach', connecting the specular reflection to the properties of the geometry of a solid surface, is reasonable and produces good results.

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http://dx.doi.org/10.1016/j.jqsrt.2013.03.007

The above-mentioned oceans and ice covered surfaces, for example, are cases where it is very natural to model the target as a surface that can be divided into small planar facets. With other, clearly particulate targets such as cirrus clouds, it can be argued that the particles (cirrus ice crystals) have planar facets that can act as mirrors. Since the ice crystals in cirrus can have sizes down to micrometer scale it might be a bit precarious to describe their facets as small mirrors, as they start to approach the wavelength size range (in visual range). Nevertheless, it seems that for example the Bennet–Porteus approximation for the strength of the specular reflection from surfaces with wavelength-scale roughness is quite accurate [6].

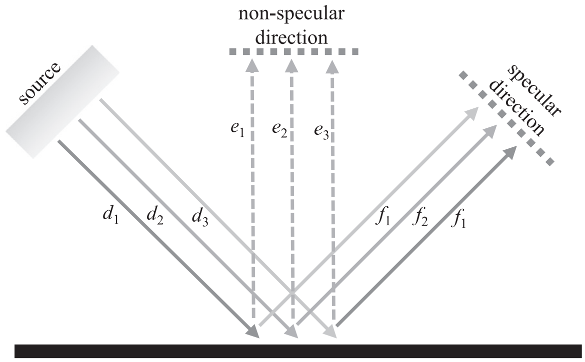

Fig. 1. Sketch of a wavefront from source to interface, and scattered waves to specular and non-specular directions.

2. Quasi-specular reflection

Industrial materials where specularity is needed often use pigments for surface finish. Pigments are quite small, usually mineral particles. The sizes can vary, but for example with high-gloss paper products the coating pigments are typically in the size range of 1–10 μm. With these small particles it is quite difficult to claim that parts of the particles surface can act as microfacets, since these parts can easily be smaller than the wavelength. Actually, the high specularity in paper products is achieved through calendering the paper with high pressure, thus organizing and packing the coating pigments into a very smooth layer. Even though the layer is smooth in macroscopic scale, in micrometer scale it still constitutes particles and there is a void space between the particles for ink to penetrate to the structure when printing.

It seems that the 'surface approach' is not reasonable in the cases where we clearly have an interface constituting wavelength-scale particles. Very glossy papers, for example, can be produced using particulate media so particulate media can produce high reflectance in the specular direction. To distinct this 'glint' or 'gloss' or 'specular-type peak' from the traditional specular reflectance from flat solid surface I will call this effect as quasi-specular reflection (QSR).

The QSR phenomenon from small particles is quite easily explained, starting from the wave-optical mechanism behind the specular reflection. The specular reflection is a simple interference of electromagnetic waves. A sketch of the process is presented in Fig. 1. When the wavefront meets the target the different parts of the wave have traveled different distances, d_1, d_2 and d_3, in the figure. Generally when the scattered wave is observed at some point, the different parts have traveled distances d_1+e_1, d_2+e_2, and d_3+e_3 which are not equal. Thus, the relative phases of the parts of the wave are different and there is no particular constructive or destructive interference. In the specular direction the distances traveled, d_1+f_1, d_2+f_2 and d_3+f_3, are all equal and the relative phases are the same, therefore constructive interference is present. The explanation behind the coherent backscattering (CB) phenomena with the reciprocal ray paths and constructive interference is actually quite close to specular reflection explanation. The differences between QSR and CB are that QSR is single-scattering effect while CB is due to multiple scattering, and that CB is valid for backscattering direction only and QSR for all specular geometries.

The specular reflection phenomenon is usually explained as above with a solid planar interface, but there are no reasons why this mechanism should not work for particles, too. Only requirement is that the particles need to be located in a plane. One could argue that in practice the particles will never be perfectly aligned in a plane, but on the other hand there are no perfectly flat surfaces either. In fact the Bennet–Porteus approximation mentioned earlier shows quite well how the specular power decreases when the surface has small-scale roughness which will effectively introduce more and more phase differences in the specular direction [6]. While the specular reflection decreases with roughness, the original specular intensity can be magnitudes larger than the diffuse component, so it will remain significant for moderately rough surfaces. The same can be true with particles, so even a small QSR contribution can stand out in the specular direction from the overall scattering pattern.

The existence of a planar or nearly planar layer of particles in the particulate media means that there is some order, some specific structure in the media. In paper coating this is formed by introducing high pressure in the top layer by calender, and in general this can be achieved by compressing the upper layer. Mechanical compression is an obvious mechanism, but also vaporizing or absorbing liquid can introduce capillary forces in the void structure and compress the media.

In what follows I will use electromagnetic wave scattering simulations to study if particulate media can create QSR. Another topic to study here is if the QSR can arise also below the very surface. Wavelength-sized particles can be quite transparent and I have noticed in previous simulations [7, Section 4.1.3] that ordered structure in the bottom of a finite-depth slab of particles can introduce intensity peak in the specular direction, and I would like to confirm that result.

2.1. Light-scattering methods

To confirm the possible QSR from particulate media I must use exact electromagnetic wave scattering methods that rely on the full treatment of the Maxwell equations. There are phase-dependent interference effects that give rise to the strong signal in the specular direction. Only