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Scalar-based speckle simulation model from the angular surface scattering based on generalized Harvey-Shack theory for laser displays☆

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ABSTRACT

A speckle simulation model based on the angular surface scattering from the analyzed rough surface is proposed for laser applications. For computationally efficient simulation model for the far-field and large-area screen, the generalized Harvey − Shack theory was used to calculate the angular scattering of rough surface that was geometrically analyzed considering the roughness and the lateral correlation length. A laser display was selected as a reference system to validate the simulation result and it was found that the proposed simulation model can generate almost similar speckle patterns with a speckle contrast ratio of 0.7095 compared to that of 0.7066 from experimental measurement.

1. Introduction

Laser-based displays have recently received much attention due to their advantages such as high illuminance, small beam size, low power consumption, and small device size [1–5]. While these devices can be used in a variety of applications, they suffer from a critical drawback related to speckles, which represent a granular intensity pattern produced by a diffuse reflection of coherent light from a non-smooth surface [5–7]. The amount of speckle pattern is usually defined in terms of the speckle contrast ratio (CR) which has a value from 0 to 1 as follows,

$$CR = \frac{\sigma}{\langle I\rangle} = \frac{\sqrt{\langle I^2\rangle - \langle I\rangle^2}}{\langle I\rangle} \tag{1}$$

where $\langle I\rangle$ and σ are the mean and the standard deviation of the intensity of a given image, respectively. Speckles degrade the quality of images produced by optical components that use coherent light sources [8–13], so the speckles must be reduced to enhance the image quality for laser display applications. For the reduced speckles, spatial and temporal coherence of a laser beam are carefully controlled by manipulating its wavelength, polarization, and angle [13].

A numerical simulation can be a good approach for better understanding about the generation of speckles from rough surfaces in a laser display. Some numerical simulations were proposed with scalar and vector calculations based on random speckle generation. In scalar-based simulations, speckles are produced theoretically using the scalar diffraction theory such as Fresnel or Fraunhofer diffraction with some assumptions, which enables computationally simple and efficient for the light propagation [14,15]. A simple scalar method was proposed by diffraction theory including random factor that represents the roughness of media expressed in phase information [14]. Another scalar speckle simulation was also reported that the proposed algorithm generates the speckles effectively using the probability density function and speckle correlation coefficient for various cases [15]. On the other hand, vector-based simulation was also used to generate speckles utilizing the electric and magnetic fields based on Maxwell's equations, which is highly accurate but computationally complex [16].

In the case of speckle simulation for a laser display, the specific surface profile and angular scattering characteristic is important to calculate the accurate speckle patterns. Because speckle occurs due to the interference between the rough surface and coherent light, speckle patterns strongly depend on the surface profile as well as detection angle from the surface. For accurate prediction of speckle patterns, thus exact surface profile must be analyzed considering specific distribution of height and lateral correlation length from the surface roughness. Also, the detection angle dependence on speckles has been analyzed and discussed [17,18]. Since a laser display is subject to the far-field and large area illumination, it is important to understand exact speckle patterns as a function of viewing angle. Thus, a new speckle simulation model is required to obtain the view angle dependence using angular surface scattering analysis from rough surfaces with exact specific profile data to be applied for a laser display.

In this paper, we propose a scalar-based simulation model for speckles using the angular scattering theory from rough surfaces. The generalized Harvey-Shack (GHS) theory was applied to evaluate the

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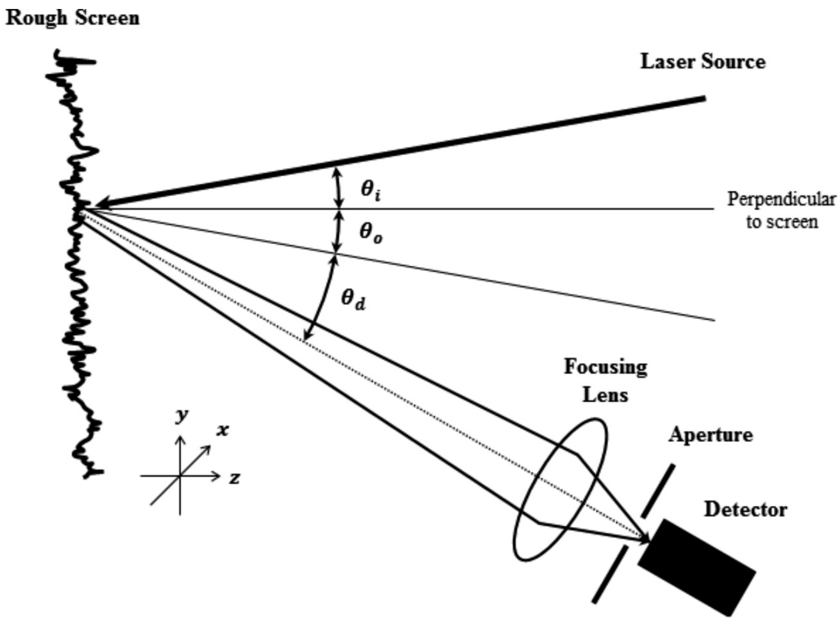

Fig. 1. Schematic of the speckle simulation model.

angular scattering characteristics of the reflected beam from the rough surface, where its geometric characteristic was analyzed from the root-mean-square (RMS) data with a concept of lateral correlation length. From the angular scattering data, speckle patterns were generated as a function of detection angle, which located long distance from the surface. To validate the proposed speckle simulation model, the simulated speckles were compared to those of the experimentally measured speckles for a laser display. Since the proposed model can realize the speckle patterns as a function of viewing angle using the scalar-based approach, it can be easily adopted for the large-area and far-field applications of laser display with a cost-effective computation.

2. GHS-based speckle simulation model

To propose and develop a speckle simulation model, we consider a system set-up for a laser display as shown in Fig. 1. Proposed simulation model was conducted by MATLAB software. First, a laser source is assumed as a Gaussian intensity distribution with changeable wavelength and incident angle θ_i. The laser beam was illuminated to the rough surface, and the surface scattering was calculated as angular distribution based on the incident angle of beam andsurface characteristics of rough screen with GHS theory. For precise speckle simulation, a rough screen was described considering the roughness and lateral correlation length. From the GHS calculation, intensity and phase of original laser beam were modulated. The modulated beam was propagated to the detector through the imaging optics of focusing lens and aperture, which has same configurations as the real speckle measurement system. To calculate the angular speckle CR, CCD camera was rotated to the screen. The detection angle θ_d was defined as an angle difference between incident angle and detector position, namely specular reflection of incident angle means 0 degree of detection angle. To realize a similar condition of human perception, an imaging optics of focusing lens and aperture was selected as f/#16 matched with detector pixel size and minimum speckle size. At last, speckle characteristics of pattern and speckle CR were calculated at various detection angles far away from the screen.

2.1. Generalized Harvey-Shack theory

It is important to understand the surface scattering characteristics in the simulation on the angle distribution of speckles generated by interference between the incident beam and the surface [19–21]. Various methods for surface scattering analysis were proposed [23–27]; among them, the GHS theory is a simplified numerical model of surface scattering based on the non-paraxial scalar diffraction scattering, which can calculate the scattering distributions of angular reflection and transmission from a rough surface. The GHS theory produces accurate scattering results for rougher surfaces than the Rayleigh − Rice model and for larger incident and scattered angles than the classical Beckmann-Kirchhoff model; thus it can be efficiently used in far-field and large-area scattering calculations [26]. First, we defined the angle parameters with subscripts of i, o, and s which are referred to the angle of incidence, the angle of specular reflection, and the angle of scattering, respectively. A Cartesian coordinated system is basically used with x, y, and z axis, and is scaled with the spatial variables that are normalized by λ, the wavelength of the light ($\hat{x} = x/\lambda$, $\hat{y} = y/\lambda$, etc.). For computational efficiency, the calculation was performed in the spherical coordinate system. To define the general spherical coordinate system, the reciprocal variables α, β, and γ are used as the direction cosines of propagation vectors to the angular spectrum of plane waves [26]. Here, α, β, and γ of direction cosines are related to the angular variables of θ and φ in spherical coordinate as following equations [26]:

$$\alpha = \sin\theta\cos\varphi, \beta = \sin\theta\sin\varphi, \gamma = \cos\theta \tag{2}$$

The rough surface is described by isotropic Gaussian height distribution, which can be defined by two relevant statistical surface characteristics; (1) the surface height distribution function, and (2) the surface auto-covariance (ACV) function C_s [26]. The GHS theory assumes that the surface heights are normally distributed as Gaussian function; thus, a surface can be parameterized in terms of the RMS surface roughness, σ_{RMS} of the standard deviation of the height distribution. The ACV function can be converted to the corresponding surface power spectral density (PSD) function by the Fourier transform, and the surface roughness values are bounded by the relevant RMS surface roughness, σ_{rel}, assuming no e7vanescent modes. And a large spatial frequency of $1/\lambda$ for the angle of incidence θ_i [26]:

$$\sigma_{rel}(\lambda,\theta_i) = \sqrt{\int_{-1/\lambda+f_o}^{1/\lambda+f_o} \int_{-\sqrt{1/\lambda^2-(f_x-f_o)^2}}^{\sqrt{1/\lambda^2-(f_x-f_o)^2}} \mathrm{PSD}(f_x f_y) df_x \mathrm{d}f_y}\,, \tag{3}$$

where f_x and f_y are the two axes of Fourier domain. f_o which is the center of the surface PSD can be expressed as

$$f_o = \frac{\sin\theta_o}{\lambda} = \frac{-\sin\theta_i}{\lambda} \tag{4}$$