Scatterers shape effect on speckle patterns

Valentin S. Denisenkov*a,b, Vadim V. Kiykoa,b, Gleb V. Vdovinb,c

aProkhorov General Physics Institute, 38 Vavilova Street, Moscow, Russian Federation 119991;
bNational Research University of Information Technologies, Mechanics and Optics, 49 Kronverksky Ave., St. Petersburg, Russian Federation 197101; cDelft University of Technology, Stevinweg 1, Delft, Netherlands 2628 CN

ABSTRACT

Laser speckle analysis is a very powerful method with various existing applications, including biomedical diagnostics. The majority of the speckle applications are based on analysis of dependence of scattered light intensity distribution from sizes of the scatterers. We propose a numerical model of speckle formation in reflected light in one-dimension which shows that properties of the scattered light are strongly dependent on the form of the scatterers. In particular, the dependence of number of speckles from the size of the scatterers was investigated for the light reflected from the surface with varying roughness; the single roughness on the surface was assumed to have the form of one-dimensional ‘pyramid’ with the sides having either linear or parabolic descent from the top of the ‘pyramid’ to the bottom. It was found that for the linear roughness, number of speckles decreased with increase of the roughness size, whereas for the parabolic roughness the number of speckles increased. Results of numerical simulation were compared with experiment investigations of roughness samples (0.5–2.5 \( \mu \text{m} \)) made of glass and copper. Due to different production processes, the glass samples are likely to have the parabolic roughness and copper samples are likely to have the linear roughness. Experiments show that the dependences of number of speckles also have different slopes, the same as in numerical simulation. These findings can lead to new analytical methods capable of determining not only the size distribution of roughness (or scatterers) but also the shape.

Keywords: laser speckles, light scattering, surface roughness

1. INTRODUCTION

Interference patterns appearing in light reflected from surfaces with a lot of statistically distributed scattering objects – speckles – are used in an increasing number of applications. For example, speckles are used in non-contact determination of surface roughness\(^1,2\), surface displacement and strain\(^3\). Biomedical applications of speckle-analysis include, for example, determination of capillary blood flow speeds\(^4\). There are several theoretical models describing speckle appearance in light reflected from the surface. The majority of the models\(^1,5,6\) describe diffraction of light by metal surfaces. These surfaces are usually obtained by machining of some kind and thus typically have surface profile with single roughness in the form of micro-pyramid with sharp edges and peaks. For other kinds of roughness shape, the theoretical models are not so accurate in describing speckle formation in the reflected light. Also, existing models don’t describe the cases when the surface is partly transparent for incidence light, which is essential for composite materials and ceramics.

In this article we present our findings regarding the role of roughness shape in the speckle-pattern formation. The dependence between structural parameters of the surface and parameters of speckle-patterns emerging in the light reflected from this surface has been investigated. We conducted experimental investigations as well as numerical modeling and then compared the results.

*denisenkov.valentin@gmail.com; phone 7 909 165-3643; gpi.ru
2. EXPERIMENT

Experimental part of our study was carried out using setup showed in Fig. 1a. The light source 1 was a laser diode providing 5 mW of radiation at 650 nm in continuous mode. The light from diode was focused using the lens 2 with 30 cm focus distance. Investigated objects were placed at an adjustable positioning stand 3. Reflected radiation was collected with lens 4, filtered with set of color filters 5 and then registered with 1/3” CCD-camera (640×480 pixels) 6. Acquired speckle-patterns were sent to PC for further processing. The example of speckle-pattern obtained in the experiment showed in Fig. 1b.

Experimental speckle patterns were analyzed to get average size of the speckle for the sample and average number of speckles. For this, threshold was chosen and the image was transformed into binary using this threshold. As a result, there was a variety of objects, properties of which were analyzed.

![Figure 1. (a) optical scheme (1 - laser, 2 - lens, 3 – positioning stand, 4 – lens, 5 – set of color filters, 6 – CCD-camera); (b) typical speckle-pattern.](image)

We used optical glass samples grinded with powders of different fineness and copper roughness samples obtained by plane polishing. Surface roughness of both glass and copper samples was measured by direct measurement on stylus profilometer. Acquired roughness parameters for the samples are shown in Table 1cvc.

Table 1. Roughness parameters for glass and copper samples.

<table>
<thead>
<tr>
<th>Glass Samples</th>
<th>Copper Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>G1</td>
<td>1.29 μm</td>
</tr>
<tr>
<td>G2</td>
<td>1.48 μm</td>
</tr>
<tr>
<td>G3</td>
<td>1.73 μm</td>
</tr>
<tr>
<td>G4</td>
<td>1.98 μm</td>
</tr>
<tr>
<td>G5</td>
<td>2.25 μm</td>
</tr>
<tr>
<td>G6</td>
<td>2.57 μm</td>
</tr>
<tr>
<td>G7</td>
<td>2.58 μm</td>
</tr>
</tbody>
</table>

3. NUMERICAL MODEL

We carried out numerical modeling of one-dimensional speckle-patterns emerging in the light reflected from the object’s surface. The incidence light was assumed to be directed along the normal to the surface.

3.1 Surface reflection

Consider object’s surface having variable height described by function h(x) showing height deviation from average level (see Fig. 2). Function h(x) has defined statistical distribution with mean value equal to zero.
Let us take the amplitude of the incidence field be equal to unity and the phase to be equal to zero at the average height level of the surface. In this case, the reflected field on the surface has the following form:

$$u(x) = u_0 e^{2jkh(x)}.$$  \hspace{1cm} (1)

where $u_0 = 1$, $k = 2\pi/\lambda$ – wave number ($\lambda$ – wavelength of incident light). Equation (1) implies that function $h(x)$ has very big impact on the form of the field on the surface and hence on the form of the field in far-field region. In order to find this form, let us find discrete Fourier transform of the field on the surface:

$$U(x) = \sum_{n=0}^{N-1} u(x_n) e^{-\frac{2\pi i n}{N}} = \sum_{n=0}^{N-1} e^{2jkh(x_n)} e^{-\frac{2\pi i n}{N}}$$  \hspace{1cm} (2)

As a result we get complex amplitude of the field in far-field region. In order to obtain the intensity we need to calculate a squared absolute value of (2), i.e. $U(x)U^*(x)$, where asterisk denotes complex conjugate. Example of simulated function $h(x)$ and speckle-pattern resulting from it are showed in Fig. 3.

![Figure 2. Example of roughness function $h(x)$ for real surface.](image1)

![Figure 3. Example of simulated function $h(x)$ (top) and resulting simulated speckle-pattern in far-field (bottom).](image2)

The size and the number of speckles in such speckle pattern depend on structural characteristics of the surface determined by the roughness function $h(x)$. 

---

**Proc. of SPIE Vol. 9333  933312-3**

Downloaded From: http://proceedings.spiedigitallibrary.org/ on 09/14/2015 Terms of Use: http://spiedigitallibrary.org/ss/TermsOfUse.aspx
3.2 Roughness function

Function $h(x)$ is crucial in speckle-pattern formation. In our work we studied the impact of this function on speckle parameters by considering two types of function $h(x)$.

Linear roughness

In this case, the function $h(x)$, i.e. the roughness on the reflecting surface, is defined as a set of ‘linear roughnesses’. In the first place, a set of random numbers $s(x_i)$, where $x_i = -10, ..., 10$ with a step of $dx = 0.001$, is chosen. These numbers are considered to have standard normal distribution. After the set is chosen, horizontal size of roughness $w$ is specified. The set $s(x_i)$ is then divided into sections of the size $w$. The mean value and the minimum value are calculated for each section. The mean value of the section is assigned to the central point, and the values in all the other points are determined by linear descend from the mean value in the center to the minimum value in the end points. As a result, we get the function $h(x)$ with the form showed in Fig. 5a.

![Figure 5a. Simulated function $h(x)$ (a) with linear shape of roughness and (b) with parabolic shape of roughness.](image)

Parabolic roughness

In this case, the function $h(x)$ is constructed in the same fashion, but this time with the parabolic descend from the central to the end points. This algorithm leads to the function $h(x)$ of the form showed in Fig. 5b.

As seen from examples of the simulated roughness functions, in the case of linear roughness we get sharp edges on the roughness peaks whereas in the case of parabolic roughness the peaks have rounded shape.

4. RESULTS

We carried out series of experiments with glass and copper samples on experimental setup, described in section 2, in order to determine the dependence between surface roughness size and speckle-pattern parameters. Fig. 6 shows
experimental dependences between number of speckles (normalized on the speckle-pattern’s mean intensity) and average roughness size in the surface plane as measured by profilometer (Table 1) obtained in the experiments.

![Graph](image1)

**Figure 6.** Experimental dependences of normalized number of speckles from surface roughness size (a) for glass and (b) for copper samples.

In Fig. 6 we can see dramatic difference between experimental dependence for glass samples and for copper ones. Existing theories of speckle-pattern formation cannot explain this fact, since according to them the dependence of speckle-pattern properties for similar sizes of roughness must be the same. The main reason for this is that the majority of the theories are focused on the surface reflection and don’t consider the shape of scattering roughnesses.

![Graph](image2)

**Figure 7.** Dependences of number of speckles from surface roughness size normalized on beam diameter obtained from numerical simulations.

To investigate the role of these factors in speckle-pattern formation we conducted numerical modeling of speckle pattern formation based on the model described in Section 3. We varied the parameter \( w \), determining the size of roughness in the surface plane. Then we modeled speckle-pattern formation for different \( h(x) \) functions resulting from different
parameter \( \omega \) and analyzed the parameters of obtained speckle-patterns. Fig. 7 shows the dependences obtained in numerical experiments for reflection from simulated surfaces having linear and parabolic form of single roughness. As can be seen from Fig. 7, there is significant difference between properties of speckle patterns formed in the light reflected from surfaces with different roughness shape.

Results of our numerical modeling show that the experimental facts can be explained if we take into account the shape of roughnesses. The dependences obtained in simulation show the same behavior and can offer a qualitative explanation of experimental results. Different slope of experimental curves appears to be determined by different shapes of roughnesses on the surface of glass and copper samples. This is, most likely, due to the different methods of processing of the samples. As a result of the processing, the glass sample surface has rounded roughnesses similar to parabolic roughness in our model, whereas the copper sample has roughnesses with sharp edges and peaks similar to linear roughness in our model. To obtain quantitative estimation from numerical model, it is necessary to continue this research. The reasonable direction for further investigations is transition to 2D model and taking into consideration the inclusions of different optical properties then the medium.

5. CONCLUSIONS

The presented results show that for successful development in practical application of speckle-analysis, it is necessary to better understand the mechanisms of reflected light formation. Our study revealed the crucial role of surface roughness shape in process of speckle-pattern formation in reflected light, which was not accounted for in earlier models. We plan to conduct further investigations in this area.

REFERENCES