Study on Deduction Method of Volume Scattering Noise of the Laser Scattering Image on the Ultra-smooth Optical Substrate Surface

Shiyi Chen¹,* , Jian Zhou¹ and Bin Zhang¹,*

¹College of Advanced Interdisciplinary Studies, National University of Defence Technology, Changsha 410073, Hunan, China.

*Corresponding author. E-mail address: kd208zb@sina.com

Abstract. In order to better observe the defects in the laser scattering image on the surface of the ultra-smooth optical substrate, the volume scattering noise needs to be deducted. This paper attempts to use three methods, which are wavelet denoising, wavelet enhancement and gradient model construction, and compares the advantages and disadvantages of the three methods.

1. Introduction

With the rapid growth of optical applications, various laser optical components put forward higher requirements for optical coating, and to achieve high-quality coating, it is necessary to support ultra-precision optical polishing process. Since this process may leave some defects on the surface of the optical substrate, these defects will directly affect the subsequent coating process, so the surface quality of the optical components must be inspected and screened. Ultra-smooth surface measurement technology has developed into many branches, such as the stylus mechanical scanning method, the optical probe method, white light interferometer, differential interference contrast microscope and atomic force microscope. In this paper, we establish a laser scattering microscope system, collect the scattering images of the substrate surface, and then analyze and process the images to realize fast judgment.

In the process of processing the laser scattering image on the surface of the ultra-smooth optical substrate, it is a very important step to deduct the volume scattering noise. Common noise types include Gaussian noise, Rayleigh noise, Erlang (Gamma) noise, Exponential noise, Uniform noise, Impulse (Salt-and-pepper) noise and so on [1-3]. The corresponding methods for eliminating these image noises are relatively mature, such as mean filter, medium filter, Gaussian filter, adaptive Wiener filter, morphological noise filter and wavelet denoising. However, different from these common noises, the volume scattering noise studied in this paper is a relatively special type of noise, and there are few literatures about its elimination methods. We attempt to use three methods to deduct the volume scattering noise, which are wavelet denoising, wavelet enhancement and gradient model construction.

2. Experimental principle

In this paper, three methods are adopted to process the laser scattering image, and several experimental principles are used as below.
2.1. Particularity of volume scattering noise
In digital images, noise mainly comes from the process of image acquisition and propagation. The performance of an imaging sensor is affected by various factors, such as the environmental conditions in the image acquisition process and the quality of the sensor elements themselves. For example, when using a CCD camera to acquire an image, the level of illumination and the temperature of the sensor are the main factors that affect the amount of noise in the resulting image. The contamination of the image during transmission is mainly due to the interference in the transmission channel. For example, images transmitted over a wireless network may be contaminated by light or other atmospheric factors. The corresponding methods for eliminating common noise are relatively mature. However, the volume scattering studied in this paper is different from these typical noises and has its own particularity.

Volume scattering is the total effective scattering produced by multi-path scattering, which often occurs when the medium is inhomogeneous or mixed. The defects in the substrate and the inhomogeneity of refractive index are the basic causes of volume scattering [4]. As shown in Figure 1, when measuring the scattering of a smooth surface, the transmitted light entering the substrate sample will be scattered when passing through the sample. It is not difficult to see that the number of particles illuminated by the transmitted light within the substrate varies in different positions and increases along a gradient from left to right. The larger the number of particles illuminated, the stronger the volume scattering occurs. Therefore, the volume scattering noise increases along the gradient from left to right.

![Schematic diagram of volume scattering](image)

Figure 1. Schematic diagram of volume scattering.

2.2. Wavelet threshold denoising and wavelet enhancement
The wavelet threshold denoising method is adopted, that is, the coefficients of each layer whose sparse modulus is greater or smaller than a certain threshold after wavelet decomposition are processed respectively, and then the denoised image is reconstructed by using the processed wavelet coefficients. The wavelet denoising process of the image signal is exactly the same as the denoising process of the one-dimensional signal. There are also three steps, and only the two-dimensional wavelet analysis tool is used instead of the one-dimensional wavelet analysis tool. Firstly, the wavelet decomposition of the
two-dimensional signal is carried out, then the high-frequency coefficients are threshold quantized, and finally the two-dimensional wavelet is reconstructed [5-7].

The principle of wavelet enhancement is shown below. Wavelet transform decomposes an image into components with different sizes, positions and directions. Before doing the inverse transform, it can change the size of some coefficients in the wavelet transform domain, and in this way we can choose to magnify the components of interest and reduce the unwanted components. The idea of enhancing the laser scattering image of the substrate is to highlight the defect characteristics and weaken the volume scattering noise. After the image is decomposed by two-dimensional wavelet, the contour is mainly reflected in the low-frequency part, while the details in the high-frequency part. Therefore, the image enhancement can be achieved by enhancing the low-frequency decomposition coefficient and attenuating the high-frequency decomposition coefficient before the inverse transform [8-10].

2.3. Least squares
Least squares is a standard method of regression analysis, which approximates the overdetermined system by minimizing the sum of the squares of residuals in the results of each equation[11]. Objectives include adjusting the parameters of the model function to best fit the data set. A simple data set consists of \( n \) points (data pairs) \((x_i, y_i), i = 1, \ldots, n\), where \( x_i \) is an independent variable and \( y_i \) is a dependent variable whose value can be observed. The model function takes the form of \( f(x, \beta) \), where a series of adjustable parameters are stored in the vector \( \beta \). The fitting degree of the model to the data point is measured by its residual, which is defined as the difference between the actual value of the dependent variable and the predicted value of the model:

\[
r_i = f(x_i, \beta) - y_i
\]

This method finds the best parameter values by minimizing the sum \( S \) of squared residuals:

\[
S = \sum_{i=1}^{n} r_i^2
\]

The model used in this paper is the straight line in two dimensions. Denoting the y-intercept as \( \beta_0 \) and the slope as \( \beta_1 \), the model function is given by

\[
f(x, \beta) = \beta_0 + \beta_1 x
\]

written in matrix as

\[
\min_{\beta_0, \beta_1} \|\begin{bmatrix} 1 & x_1 \\ \vdots & \vdots \\ 1 & x_2 \end{bmatrix} \begin{bmatrix} \beta_0 \\ \beta_1 \end{bmatrix} - \begin{bmatrix} y_1 \\ \vdots \\ y_2 \end{bmatrix} \|_2 = \min_{\beta} \| A \beta - Y \|_2
\]

Directly give the parameter solution of equation (4):

\[
\begin{align*}
\beta_1 &= \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n} (x_i - \bar{x})^2} \\
\beta_0 &= \bar{y} - \beta_1 \bar{x}
\end{align*}
\]

where

\[
\begin{align*}
\bar{x} &= \frac{1}{n} \sum_{i=1}^{n} x_i \\
\bar{y} &= \frac{1}{n} \sum_{i=1}^{n} y_i
\end{align*}
\]

3. Experimental system for image acquisition
In this paper, the process of collecting the laser scattering image on the surface of the ultra-smooth optical substrate is completed with the help of the laser scattering microscope image acquisition system
designed and built by the authors themselves. The overall design and workflow of the experimental system are shown in figure 2. In the inspection process, because the laser beam is always fixed, the computer-controlled X-Y translation stage will move along a predetermined path to detect the area to be measured point by point. Scattering images are collected each time it moves to a designated location to illuminate a specific area. After a round of movement, the final laser scattering image of the substrate surface can be obtained by cutting and stitching different small images at different scanning positions.

![Figure 2. The workflow chart of the mechanical part of the system.](image)

A set of laser scattering images were obtained by testing the optical substrate samples. The bright spots on the dark background of the images correspond to the defects on the substrate surface. The typical Substrate A is selected as the object of subsequent image processing, as shown in figure 3. Since there are four scanning paths, the volume scattering noise in each column increases along a gradient from left to right, so the volume scattering noise distribution of the image is in the form of four steps.

![Figure 3. The laser scattering image of Substrate A.](image)

4. **Experimental results of image processing**

Three methods are used to process the laser scattering image on the surface of Substrate A.
4.1. Image denoising with wavelet function

There are different wavelet functions can be used for wavelet denoising, and in this paper, we try to process the image with sym4 and coif2 wavelet function.

Select Substrate A as an example for analysis, and the image is decomposed by using sym4 wavelet function. To make the observation more intuitive, the three-dimensional images of the gray distribution corresponding to the pre- and post-processing images are made, as shown in figure 4. As can be seen from figure 4, the image is decomposed into two layers by means of sym4 wavelet function. Compared with the original image, the reconstructed image of the first layer has little change, and several spots on the substrate can be clearly identified by observing the three-dimensional image of the gray distribution. The volume scattering noise of the reconstructed image of the second layer is weakened to some extent, and the spots can be clearly observed to analyze the defects of the substrate, but the gray value has a certain degree of distortion compared with the original image. Then, use coif2 wavelet function to decompose the image, and Select Substrate A as an example similarly. To make the observation more intuitive, the three-dimensional images of the gray distribution corresponding to the pre- and post-processing images are made, as shown in figure 5. As can be seen from figure 5, the image is decomposed into two layers by the coif2 wavelet function, and the images after the first and the second denoising processing are not obviously different from the original image. The volume scattering noise changes little, but it is not difficult to distinguish the spot distribution clearly.

It is found that the effect of noise reduction by using sym4 wavelet function and coif2 wavelet function is not obvious. That’s because the main noise of the laser scattering image of the ultra-smooth optical substrate is not high-frequency white noise, but a regular gradient noise.
Figure 4. Image denoising with sym4 wavelet function. 
(a) Original image. (b) Three-dimensional gray-scale image of figure 4a. (c) Reconstructed image of the first layer. (d) Three-dimensional gray-scale image of figure 4c. (e) Reconstructed image of the second layer. (f) Three-dimensional gray-scale image of figure 4e.
4.2. **Image enhancement with wavelet analysis**

In the same way, we choose Substrate A as an example to analyze, and use wavelet analysis to enhance the image. To make the observation more intuitive, the three-dimensional images of the gray distribution corresponding to the pre- and post-processing images are made, as shown in figure 6. By processing the wavelet coefficients, the enhancement effect shown in figure 6 can be obtained. Obviously, the volume scattering noise has been weakened to a very low and very gentle level, and the main defects of the substrate are highlighted in the form of bright spots. However, the disadvantage is that it is particularly difficult to find a perfect coefficient to ensure that all the defect features are not lost while volume scattering noise is removed.

---

**Figure 5.** Image denoising with coif2 wavelet function.

(a) Original image. (b) Three-dimensional gray-scale image of figure 5a. (c) Image after the first denoising processing. (d) Three-dimensional gray-scale image of figure 5c. (e) Image after the second denoising processing. (f) Three-dimensional gray-scale image of figure 5e.
4.3. Image denoising with gradient model construction

It can be seen that the laser scattering image of the substrate sample shown in figure 3 has four bands of similar gradient volume scattering noise. In view of the noise characteristics, a corresponding model is constructed. The general idea of establishing the gradient model is to select the region without obvious defects as the raw data of volume scattering noise model, calculate the average gray value of each column of pixels, and divide the data into four groups (that is, four column scanning bands) for linear fitting by using the method of least squares. The data obtained by fitting is used as the gray value of each column, and the volume scattering noise model is established accordingly. The resulting gradient model of volume scattering noise is shown in figure 7. Substrate A is selected and processed to deduct the volume scattering noise model, and the three-dimensional images of the gray distribution corresponding to the pre- and post-processing images are made, as shown in figure 8. The laser scattering image and its corresponding three-dimensional image of the gray distribution after processing are compared to the original ones. In the processed image, the surface is generally flatter and the defects are much more prominent than before.
5. Conclusion

In this paper, three methods are used to deduct the volume scattering noise of the laser scattering image on the surface of the optical substrate, and each method has its own merits, that is, the denoising with wavelet function (sym4 and coif2), the enhancement with wavelet analysis and the denoising with gradient model construction.

Using sym4 wavelet function can attenuate the volume scattering noise to a certain extent, and clearly observe the defects of the substrate, but there exists some distortion in the gray value. Coif2 wavelet function doesn’t work very well when used for image denoising, but we can still distinguish the defects clearly. Using wavelet analysis can obviously weaken the volume scattering noise, but at the same time weaken the defects with low brightness, and only amplify the defects with high brightness. Constructing a gradient model for noise reduction is more suitable for the specific volume scattering noise characteristics of the optical substrates in this paper, which can weaken the volume scattering noise while highlighting the defect features.

References

[1] Grant M 2020 Nature Chemical Biology 16(2) 106
[2] Wang S, Wang W, Duan S, Wang L and Chi K 2018 Information Sciences 61(12) 214
[3] Bai L 2019 Computers & Mathematics with Applications 77(10) 2627
[4] Wei Z 2012 Research on Scatter Measurement of Supersmooth Substrate Surface (Changsha: National University of Defense Technology) (in Chinese)
[5] Kuljeet K and Baljit S K 2016 International Journal for Science and Advance Research in
[6] Chabchoub S, Mansouri S and Ben S R 2016 Australasian Physical & Engineering Sciences in Medicine 39 655
[7] Li G, Li H and Wang L 2012 Journal of Nantong Textile Vocational Technology College 2 14
[8] Brindha C, Thangavel K and Sasirekha K 2015 Indian Journal of Engineering 12 6
[9] Manohar A and Lanza F 2014 Experimental Techniques 38 28
[10] Stuti G and Paresh R 2017 International Journal of Advance Research in Science and Engineering 6 9
[11] Trad and Daniel 2020 Geophysical Prospecting 68(3) 804