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RETRIEVING THE SURFACE RELIEF COMPONENTS USING PHASE-SHIFTING INTERFEROMETRY AND GAUSSIAN FILTER

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It is known that for the determination of mechanical, corrosive and tribological parameters, such terms as “roughness” and “waviness” are often used. Filtering in the frequency domain is used to extract these components from the total relief. An approach to determining the optimum value of the cut-off frequency for 2D Gaussian filter is proposed to obtain the surface relief by three-step phase-shifting interferometry with an arbitrary phase shift of the reference beam.

Keywords: *2D filtering; interferometry; surface relief; roughness; waviness.*

ВІДНОВЛЕННЯ КОМПОНЕНТІВ РЕЛЬЄФУ ПОВЕРХНІ ЗА ДОПОМОГОЮ ФАЗОЗСУВНОЇ ІНТЕРФЕРОМЕТРІЇ ТА ГАУССІВСЬКОГО ФІЛЬТРА

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Для відновлення компонентів шорсткості та хвилястості зі загального рельєфу використовують фільтрацію в частотній області. Запропоновано підхід для визначення оптимального значення частоти відсічки для 2D-гауссівського фільтра, щоб отримати рельєф поверхні за допомогою трикрокової фазозсувної інтерферометрії з довільним зсувом фази опорного пучка. Розраховані так компоненти поверхні придатні для визначення механічних, корозійних та трибологічних параметрів матеріалу.

Ключові слова: *2D фільтрація; інтреферометрія; рельєф поверхні; шорсткість; хвилястість.*

Investigation of the surface relief of the material surface is an actual task for the control and evaluation of the quality of the assemblies under the static and cyclic loads or in an aggressive media. At the same time, informative parameters can be both surface macro- and micro-relief. Various methods are used for retrieving the total relief, which can be divided into contact and non-contact ones. Among the non-contact methods, the most widely used today are SEM [1], digital holography [2], and phase-shifting interferometry (PSI) [3]. We propose a new approach to the reconstruction of the surface relief using the three-step phase-shifting interferometry method with an arbitrary phase shift of the reference beam [4]. This method allows the extraction of the surface relief components using two sequential iterations with filtration in the frequency domain (FFD).

At the stage of separation the roughness and waviness components, there is a problem of choosing the optimal filters and their parameters. In the three-step method the problem is complicated, since the filtration procedure must be applied twice. Therefore, in this paper we consider the application of 2D Gaussian filter to separate the components of a total surface relief, namely 3D surface roughness and 3D waviness, by the three-step PSI method. By retrieving the surface relief components from the simulated test phase map and comparing them to initial ones, the optimal parameters for this filter are selected and an approach that can be used for other 2D filters is proposed.

Mathematical description of the tree-step PSI method. The essence of the three-step phase-shifting interferometry method consists in sequentially recording of three digital interferograms $I_n(x, y)$ with an arbitrary phase shift of the reference beam. The phase map of the surface relief is obtained using the following relation:

$$\varphi(x,y)=\arctan\left(-\frac{c}{b}\right), \tag{1}$$

where:

$$b=\left[I_1(x,y)-I_3(x,y)\right]\sin\alpha_{21}+\left[I_2(x,y)-I_1(x,y)\right]\sin\alpha_{31}, \tag{2}$$

$$c=\left[I_2(x,y)-I_3(x,y)\right]+\left[I_3(x,y)-I_1(x,y)\right]\cos\alpha_{21}+\left[I_1(x,y)-I_2(x,y)\right]\cos\alpha_{31}. \tag{3}$$

The value of the phase shift αn1 between two interferograms is obtained from:

$$\alpha_{n1}=\arccos\frac{\left\langle\left[I_1(x,y)-\left\langle I_1(x,y)\right\rangle\right]\left[I_n(x,y)-\left\langle I_n(x,y)\right\rangle\right]\right\rangle}{\sigma_{I_1(x,y)}\sigma_{I_n(x,y)}}, \tag{4}$$

where σ denotes standard deviation.

The obtained surface phase map contains information about the 3D roughness and waviness of the object. After that the surface relief components are obtained using the FFD with two iterations according to the algorithm given in [4]. At the first iteration, the FFD is applied to the continuous cos and sin components of the phase map. At the second iteration the 3D roughness and waviness components are separated. Moreover, the roughness is calculated by subtracting the resulting waviness component from the initial surface relief.

Obviously, during the relief components retrieving by this method it is important to choose the optimum cut-off frequency f_c at each iteration step.

Description of considered 2D filter. In general case the FFD of initial image $F(x, y)$ can be described by the following equation:

$$F'(x,y)=FFT^{-1}\left\{G(x,y)\cdot FFT\left\{F(x,y)\right\}\right\}, \tag{5}$$

where $FFT\{\dots\}$ denotes fast Fourier transform; $G(x, y)$ represents the transfer function.

We propose to use the Gaussian filter for extraction of 3D surface roughness and waviness from a retrieved surface relief because this filter is often used to perform the specified operation. In this case this filter should be two-dimensional, that is

$$G_{Gauss}(x,y)=\exp\left[-\frac{u^2+v^2}{D_0{}^2}\right], \tag{6}$$

where u, v are the image coordinates in the frequency domain

$$D_0=\sqrt{u_c{}^2+v_c{}^2}\,. \tag{7}$$

The 3D representation of the Gaussian filter is shown in Fig. 1.

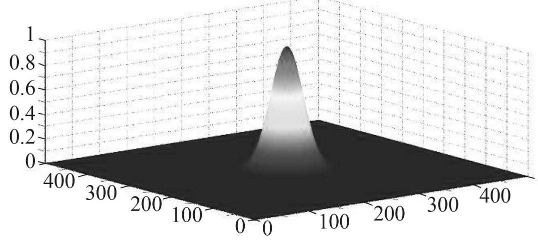

Fig. 1. General view of the 2D Gaussian filter.

Using the proposed filter a technique for determination of the optimal values of the cut-off frequency is developed.

Description of the technique for determination of the optimal cut-off frequency. To implement the proposed technique a test surface was produced. It contained the 3D surface waviness $w(x, y)$ and 3D surface roughness $r(x, y)$ components. The waviness component was obtained using standard function "peaks" with dimension 500×500 pixels. The roughness component was obtained by adding Gaussian noise with a value ±0.065 μm. The general view of the test surface is shown in Fig. 2.

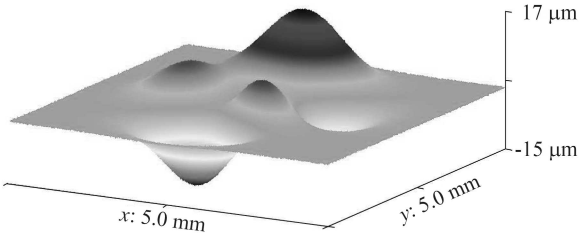

Fig. 2. Test surface.

After that the phase map of the test surface (see Fig. 3.) is obtained using conventional formula for retrieval of a phase map that is

$$\varphi(x, y) = \arctan\left(\frac{\mathrm{Im}\left(\exp\left[iT(x, y)\right]\right)}{\mathrm{Re}\left(\exp\left[iT(x, y)\right]\right)}\right), \tag{8}$$

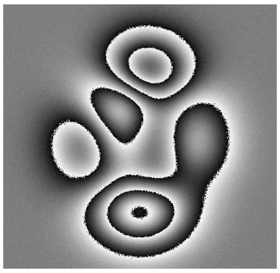

Fig. 3. Phase map of the test surface.

where $T(x, y)$ stands for the total relief, which consist of 3D roughness and waviness components.

Using the obtained phase map the relief components of the test surface were separated by the double iteration algorithm described in the previous section. For estimating the errors the standard deviation between the initial relief components and those obtained by our algorithm was considered. At each iteration step the value of f_c for the Gaussian filter was set within the range 0.0012…0.021μm^{-1}.

Results and discussion. It is established that the error value is rather small and varies insignificantly within the entire proposed frequency range. Starting from 0.002 μm^{-1} a rapid error increase is observed. However, for the first iteration step the smallest value of the error for 3D surface roughness and waviness is achieved at a cut-off frequency close to this region (f_{c1} = 0.0188 μm^{-1}).

A quite different situation is observed when choosing the optimum cut-off frequency for the second iteration step. The features of the interconnection between the cut-off frequencies on two iteration steps are shown in the graph in Fig. 4. Here the cut-off frequencies at the first iteration step (x-axis), and the appropriate cut-off frequencies at the second iteration step, for which the minimum error is achieved, are shown.

From the following graph it is seen that at the second iteration step almost for any value of f_{c1} optimal cut-off frequencies for the roughness and waviness components do not match and are equal to f_{c2} = 0.009 μm^{-1} and f_{c2} = 0.0136 μm^{-1}, respectively. The intersection of two curves is located at a point where the standard deviation significantly increases.

However, the proposed approach with standard deviation does not provide the full information about separation errors. During the determination of the relief components with decreasing f_{c2} some distortion of the surface roughness occurs. In this case a certain part of the waviness component appears in the roughness. In the frequency domain this feature causes the increase of the central peak height. Thus, two Fourier spectra of the separated roughness components (using two obtained values of f_{c2}) were calculated (see Fig. 5).

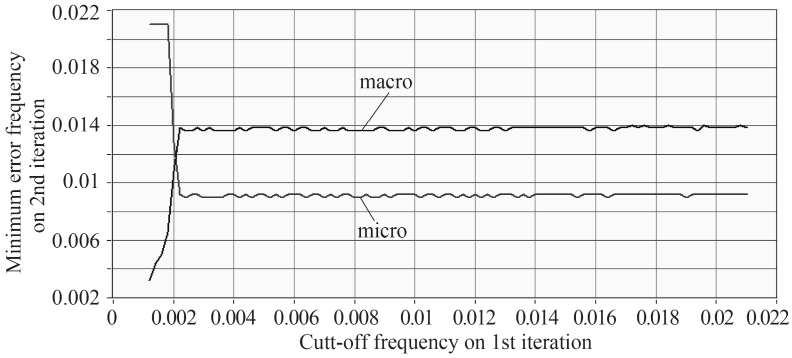

Fig. 4. Interconnection of the cut-off frequencies at first and the second iteration steps.

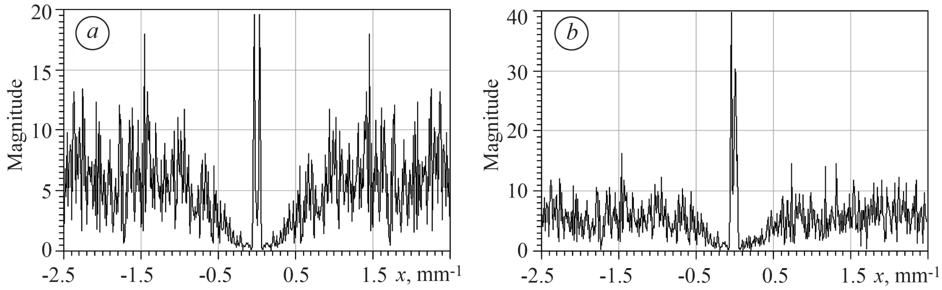

Fig. 5. Spectra of the 3D roughness components obtained
with f_{c2} = 0.0136 μm^{-1} (*a*) and f_{c2} = 0.009 μm^{-1} (*b*).

From Fig. 5 one can observe that despite at 0.009 μm^{-1} minimum standard deviation value is provided, the retrieved 3D surface roughness is disturbed due to the presence of the surface waviness part. That's why a standard deviation of the roughness component cannot be used as the main criterion in the determination of the optimal cut-off frequency at the second iteration step.

CONCLUSION

The technique for the determination of the optimal values of the cut-off frequencies was developed and proposed for three-step phase shifting interferometry. Optimal cut-off frequencies for the 3D roughness and waviness components of the test surface were determined using the least-error approach. The results showed that for the 2D Gaussian filter standard deviation of micro-relief could not provide the optimal cut-off frequency determination due to the distortion on the macrolevel. This approach will be used for other 2D filters to improve the understanding of the relief components separation procedure.

1. *Surface* roughness standards, obtained with the scanning tunneling microscope operated at atmospheric air pressure / N. Garcia, A. M. Baró, R. Miranda, H. Rohrer, C. Gerber, R. G. Cantu, J. L. Pena // Metrologia. – 1985. – 21 (3). – P. 135.
2. *Picart P., Li J. C.* Digital holography. – John Wiley & Sons. – 2013.
3. *Schreiber H., Bruning J. H.* Phase shifting interferometry // Optical shop testing. – 2007. – P. 547–666.
4. *Three-step* interferometric method with blind phase shifts by use of interframe correlation between interferograms / L. I. Muravsky, A. B. Kmet, I. V. Stasyshyn, T. I. Voronyak, Y. V. Bobitski // Optics and Lasers in Engng. – 2018. – **105**. – P. 27–34.

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