Reduction of speckle noise in laser energy distribution on the target by means of modified Fourier hologram and incoherent averaging technique

A.G. Derzhypolskyi, O.V. Gnatovskyi, L.A. Derzhypolska

Institute of Physics, NAS Ukraine, 46, prospect Nauky, 03680 Kyiv, Ukraine
Correspondence author: phone +38-(044)-525-99-68, e-mail: derzh.l@iop.kiev.ua

Abstract. Presented in this paper is the technique of formation of required laser intensity distribution on the target with a reduced speckle noise. The method is based on the use of modified Fourier hologram adapted to controlled phase modulators. Reduction of the speckle noise in the laser energy profile is obtained using multiple incoherent superposition of synthesized holographic images. Each hologram is synthesized with different random diffuser. The advantages of this method: relative simplicity of hardware; robustness with regard to distortions of any kind in input beam and/or optical path of the scheme; controlled reduction of the speckle noise in the final energy distribution.

Keywords: Fourier holography, holographic image formation, speckle noise, spatial light modulator.

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1. Introduction

Development of methods enabling to form a given amplitude-phase distribution of laser radiation on the target is the actual problem of science and technology. This is applicable in many areas including medicine, biology, nanophysics, technology for manipulating objects of different nature, size and shape [1], material processing, photolithography [2, 3] and other tasks. Very often, these problems are considered in context of presence of some distortions or aberrations introduced mostly, but not solely, by a transfer medium [4, 5]. An efficient instrument used for these tasks is spatial light modulator (SLM) device that is essentially the controlled amplitude or phase transmitter based on liquid crystal or micromechanical elements. The use of SLM allows creating dynamically controlled holograms in real time for shaping or modulating the light beams for the purpose of the set task.

We consider here formation of the desired intensity distribution on a target using SLM in the presence of aberrations. If phase information is not important for studies, and only intensity is of interest, then to create a hologram it is possible to apply a random phase diffuser (RPD). This allows the hologram to become less susceptible to deformation (in particular, the loss of its parts) when the image is restored. Restoration of a hologram with an aberrated beam necessarily distorts the restored image. But if the hologram is recorded or synthesized using RPD, the restored image integrity insignificantly improved against the aberrations in restoring beam [6]. However, another problem arises then – the speckle noise. The goal of this work is to develop a method of eliminating or at least reducing the speckle noise in the image stabilized by means of [6].

2. The problem

As demonstrated in [6], the use of RPD for producing either real or synthesized Fourier-hologram makes a significant stabilizing effect against aberrations in the restoring beam. In a common case, the resultant intensity distribution formed by Fourier-holography scheme is described as:

$$I_c = |a * h|^2 , \qquad (1)$$

where a is the amplitude of the original (required) image, h – hardware function of the system and * – convolution operator. In this case, the output intensity distribution is particularly sensitive to any phase aberrations in the system due to coherent (amplitude) type of convolution. The hardware function h in case of phase distortions in the system is complex and causes a significant skew in the intensity distribution due to interference.

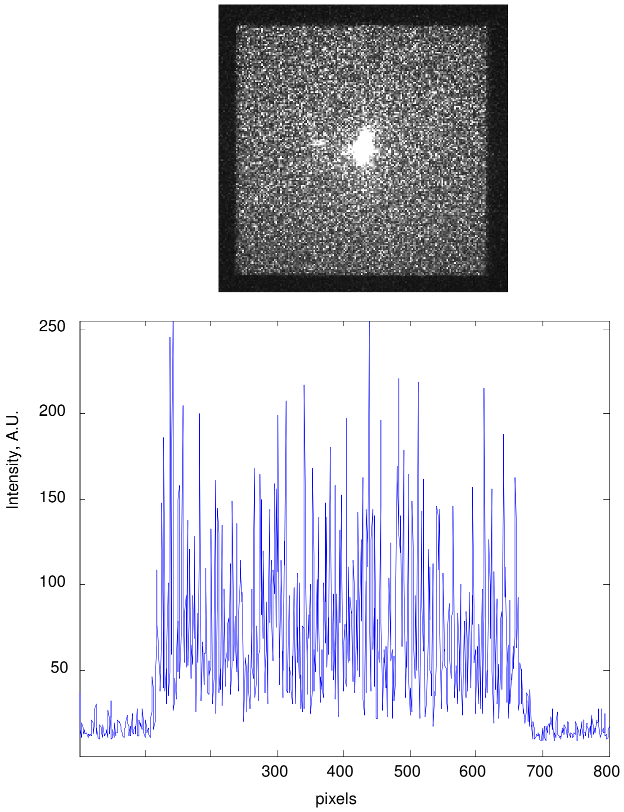

Fig. 1. Real image (a rectangular intensity step) formed by transmitting SLM with binary Fourier hologram synthesized with RPD (visual representation on the left and the plot of intensity on the right).

But the use of good RPD with relatively small radius of correlation converts the convolution type from coherent (amplitude) to quasi-incoherent (intensity):

$$I_c \cong |a|^2 * |h|^2 . \tag{2}$$

In this case, because of incoherent convolution, the output image appears highly insensitive to phase aberrations. The function $|h|^2$ is real and positive as well as $|a|^2$, so there are no significant changes in the intensity distribution, even if severe phase distortions occur.

However, there is another problem with RPD. Despite the output image is strongly stabilized, it is covered with speckles, which may be undesirable. Fig. 1 shows a simple intensity distribution (a rectangular flat intensity step) formed by spatial light modulator with binary Fourier-hologram (0 and π phase values that correspond to ± 1 amplitude transmission values) synthesizer with RPD. It is obvious that though the envelope form of distribution is as the required one, but the filling is messed up with speckle noise. Formation of speckle pattern is inherent to RPD, as it always has a finite radius of correlation. So, the coherence of the waves forming the output image causes the residual interference within the radius of correlation producing a speckle pattern. This effect is especially notable in the case of synthesized holograms as the radius of correlation of digital RPD is limited by the pixel pitch.

From numerous experiments, we know that the speckle pattern of each particular image is stable in time and is defined by RPD used. This fact is used to build a solution to the speckle problem.

3. The solution

The speckle pattern is the noise in output image (signal). The basic and common solution to reduce the noise is to average multiple samples of the signal. In the case of independent and random noise in every sampled signal, the expected reduction of noise level is proportional to the square root of the number of samples. In this case, the noise (speckle pattern) in the signal (image) is defined by used RPD. So, to achieve noise reduction from averaging, we should take every new image generated with another independent RPD. Similar approach of the use of RPD together with incoherent averaging is used successfully in [7] for imaging through scattering medium and also in [7-10] for improvement of image quality from digitally reconstructed real holograms.

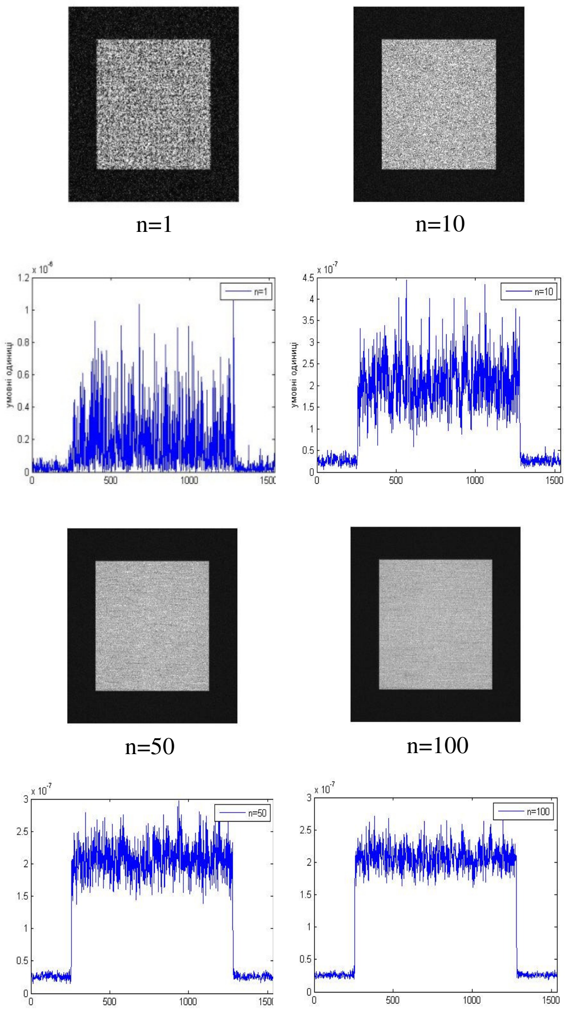

Fig 2. Speckle pattern reduction with the number of averaged samples. The computational experiment (visual representation above and intensity graphs below).

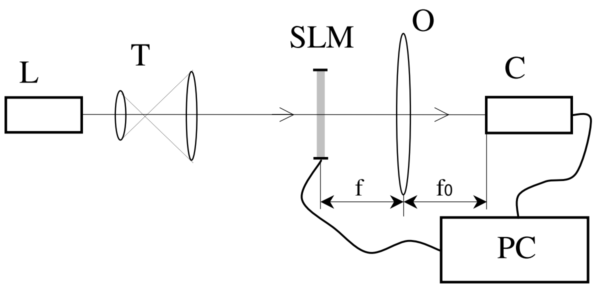

Fig. 3. Experimental setup with SLM. L – solid state laser (532 nm); T – telescope (beam expander); SLM – phase transmittance spatial light modulator; O – Fourier-objective; C – CCD-camera; PC – controlling PC.

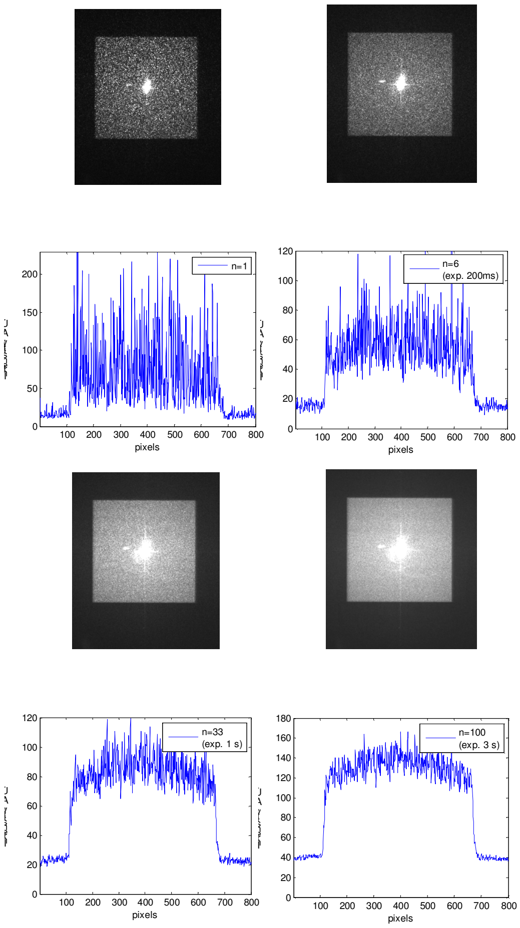

Fig 4. Speckle pattern reduction with the number of averaged samples. The real experiment with synthesized holograms and SLM (visual representation above and intensity plots below).

3.1. The computational experiment

First, the computational experiment was made to check the expectations. In MatLab environment, multiple binary Fourier-holograms of square flat-top intensity step with independent random RPDs were synthesized and saved for further use by means of iterative algorithm. Type of image was chosen for further clear calculation of signal-to-noise ratio (SNR). The binary type of hologram was chosen because of two reasons: 1) to test the method on a simplest possible type of hologram, and 2) because of limitation of displaying hardware available. All the holograms were then digitally reconstructed in MatLab, and output images were averaged. Fig. 2 represents the results of computational experiment with 1, 10, 20, 50 and 100 samples averaged. A significant noise reduction is visible both in the pictures and the intensity plots.

3.2. The real experiment

The second stage of the work was the real experiment with synthesized holograms. To perform this used was the setup shown in Fig. 3 (polarizer and analyzer required for switching to the phase modulation mode, and neutral density filters are omitted for visual simplification).

100 synthesized binary holograms with independent RPDs were sequentially displayed using SLM (HoloEye HEO-0017, 1024×768 pixels, transmittance mode) with an average rate of 33 fps. The averaging factor was tuned by means of exposure time of the camera. The calculated averaging factor n = (Exposure × Frame rate). Experiments were performed with a single picture (averaging factor $n = 1$), and exposure times 200 ms ($n = 6$), 500 ms ($n = 17$), 1 s ($n = 33$) and 3 s ($n = 100$). Averaging factor estimation was not accurate, as the frame rate was not controlled and thus might not be strictly constant. The results together with the intensity plots are shown in Fig. 4. The intensity plots were produced from the side section (non-central) of corresponding image to avoid the central intensity peak.

This peak is inherent to the use of SLM. It contains non-diffracted light caused mostly by the fill factor of SLM. The solution to this issue is the use of patterns utilizing peripheral part of diffraction field and omitting the center. Or, probably, SLM technology will be enhanced to eliminate this fill factor problem. Apparent curvature of the average intensity line reveals a slight vignetting in the image caused by diffraction of light on the aperture of single pixels of SLM. This was taken into account when calculating the results. This effect also could be reduced on the stage of generating the hologram by means of incorporating an inverted single-pixel diffraction function. Like to the computational experiment, improvements in speckle noise are visible both in the pictures and intensity plots.

3.3. Visual effect

To illustrate a visual effect of the method on the generated images, a realistic gray-scale image was taken and real experiment performed with the maximum averaging factor of 100. Because of the fundamental restrictions of binary hologram, one cannot use the whole diffraction field for the generated image unless it is center-symmetric. Thus, a full phase hologram was used for generation. However, since the maximum available phase modulation value at the hardware used is only 1.4π and not 2π, the overall image quality is compromised. The result is shown in Fig. 5. Enhancement of the details is also shown in enlarged areas.

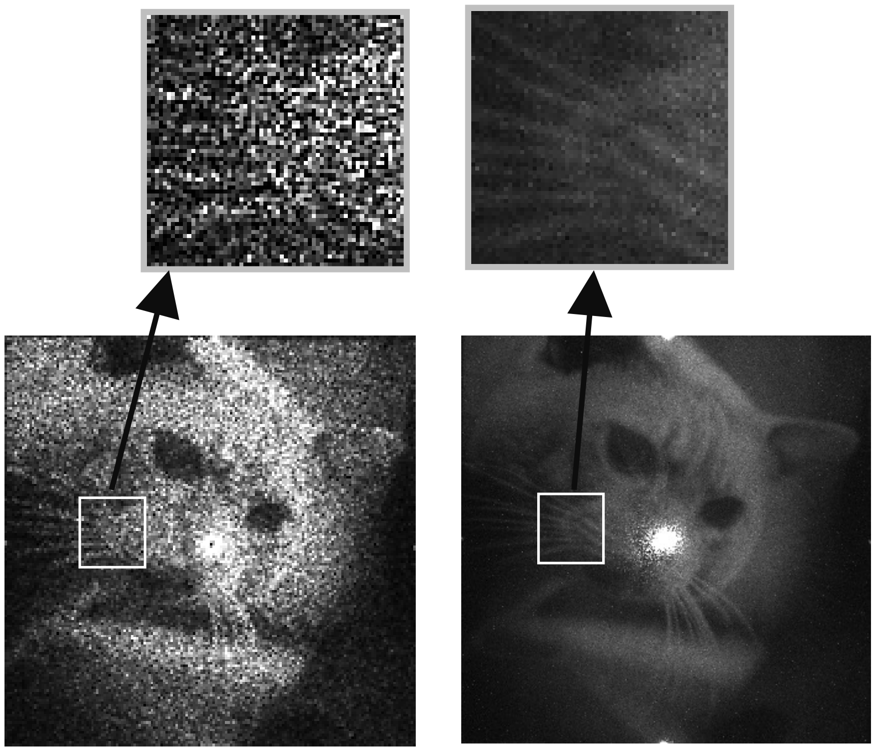

Fig. 6. Visual enhancement of the image generated by pure digital hologram with RPD by incoherent averaging. The averaging factor n = 1 (left) and n = 100 (right).

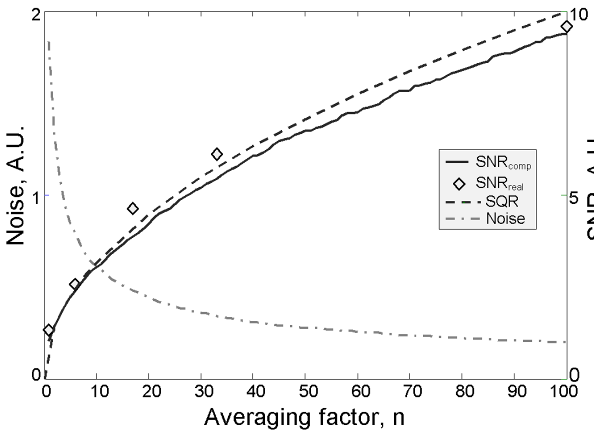

Fig. 5. SNR improvement with the number of averaged samples. SNR_{comp} and SNR_{real} are the calculated signal-noise ratios from computational and real experiments, accordingly; SQR – expected theoretical curve for SNR; Noise is the noise calculated from the computational experiment.

3.4. Calculation and discussion of the results

For numerical characterization of the results, SNR has been calculated in every case. The signal is defined as an average on the top of the intensity step after subtraction of the background value (downhill of the intensity step). The noise is defined as a standard deviation of the signal on the top of intensity step. In real experimental data, an additional correction for the single-pixel diffraction function is applied after subtraction of the background. Displayed in Fig. 6 are the calculated results. Both computational and real experiments are presented along with the theoretical expectance curve. For the computational results, it was possible to calculate SNR after each new averaging iteration. So, the corresponding curve is solid. While for the real experiment, only certain points are available. Displayed also is the noise curve from the computational experiment, for illustration purposes only.

As seen from Fig. 6, both computational and real data are quite close to the theoretical expectance curve. Observed systematic deviation of SNR_{comp} curve from the theoretical one could probably be caused by not completely independent RPDs. As those have been produced by pseudo-random number generator and could have some residual correlation. Another reason may be is not clearly established relation between the signal and background. So, the signal level might be underestimated.

For the SNR_{real} points, it should be noted that their positioning on x-axis is not accurate. As the averaging factor calculation is based on holograms displaying frame rate, which is known only as average and could deviate during the experiment. Nevertheless, the trend is very close to theoretical expectance.

4. Conclusion

Formulated in the work is the problem of speckle noise in intensity distributions formed by holograms created using RPD. Offered here is the solution to this problem as based on the well-known principle of averaging the samples of the same signal with independent random noise. Basic experimental implementation of the solution is provided with averaging factor of up to 100 showing significant improvement of image quality. With more fast-acting specialized equipment, an averaging factor of 1000 or even more is achievable. Taking into account high robustness of image formation by holograms created with RPDs, particularly against aberrations, the combination of these two methods could be extremely useful in a wide range of tasks to form the required intensity distribution. The proposed method is virtually unconstrained in terms of enhancement of final image/intensity distribution, however for the cost of time. So, for practical means, especially for dynamic applications, further attention will have to be paid to the time consumption issue. A maximum achievable resolution will also have to be investigated.

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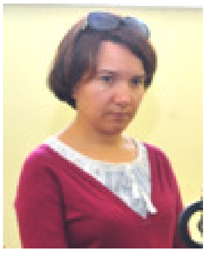
Authors and CV

Andrii G. Derzhypolskyi. Currently, Andrii is Researcher at the Institute of Physics, NAS of Ukraine. Authored of 22 scientific publications and 1 patent. The area of scientific interests is correlation optics, laser technology, optically inhomogeneous objects.

Olexandr V. Gnatovskyi. PhD and Senior Researcher at the Institute of Physics, NAS of Ukraine. Authored over 200 articles, 33 patents. The area of his scientific interests is investigation of correlation methods for formation and use of laser beams with controlled spatial angular characteristics.



Liudmyla A. Derzhypolska. She is PhD and Senior Researcher at the Institute of Physics, NAS of Ukraine. Authored 15 scientific publications. The area of scientific interests is correlation optics, holographic interferometry, speckle-interferometry and optically inhomogeneous objects.