REAL WAVE RECONSTROCTION IN COMPUTER AND DIGITAL HOLOGRAPHY

PhD thesis

ZSOLT PAPP

Budeset University of Technology and Economics

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Introduction

The first holograms were performed in 60's after the appearance of lasers. High resolution photographic plates are usually used to record the interference pattern of the object wave and reference wave in optical holography. After the exposure the holographic plates are generally developed by chemical processes, and the reconstruction can be managed by the application of the reference beam. (The 3D object itself is required to generate the object wave in exposition.)

The computer holography provides with new possibilities. The hologram can be recorded without the existence of the real object, only the analytical description of its surface is needed. The first computer-generated holograms were produced also in 60's. In the first 2 or 3 decades mainly the Fourier-type holograms were developed, because the law computation process – FFT – could be used for generating holograms and the reconstruction could be calculated by the application of inverse FFT. The Fourier-type holograms have two disadvantages: 2D objects can be reconstructed only, and a real optical element (lens or objective) is required for reconstruction, too. The non-Fourier-type hologram records the information of the complex amplitude of the object wave of a 3D object and doesn't need any optical element to reconstruct the real object beam. In spite of the advantages, the non-Fourier-type holograms have been developed just in the last 10 years, because of the large computational requirements in simulations. The appearance of fast computers (and PC-s) gave the possibilities for numerical investigations of non-Fourier-type holograms, too.

Not only the matrix elements can be calculated by the use of fast computers, but the reconstruction can be simulated, too. The numerical modeling of reconstruction can be very useful for example in optimization of kinoform lenses. In digital holography the hologram is recorded by a CCD camera connected to a computer. The reconstruction of the real object wave can be simulated by numerical methods or can be managed by an SLM device in the real space.

Aims

It was proposed to develop a numerical method simulating the exposure and reconstruction of non-Fourier-type computer-generated holograms. On behalf of this aim it is useful to investigate how the image fidelity of the reconstructed object depends on the parameters of the holograms. A new algorithm had to be developed to decrease the calculations. The aim was to work out an estimating formula for the statistical treatment (estimation) of the numerical results. It was proposed to use the developed method(s) to a practical problem, too. I have planned to apply the simulation method in digital holography. A simple holographic arrangement for recording the interference pattern (of the hologram) can be hardly adopted. This is the reason why a new exposure technique and new algorithm (for phase recovering) are needed to be developed.

Applied methods and devices

The research works were done at Department of Physics of Budapest University of Technology and Economics in the Group of Optical Metrology. Some computer programs for modeling the reconstruction were written in program language of Turbo Pascal. The running of these software were carried out in a Silicon Graphics workstation with the help of Nándor Bokor PhD student. Other parts of the computations were written in Visual Basic program language, and was a simple Pentium-4 PC used. The optical arrangements were constructed in the optical laboratory of the Dept. of Physics. In the beginning I used a He-Ne laser (20mW) and later I applied an Ar-ion laser. A CCD camera (1024x1024 pixels, 10 bit) was used to record the digital holograms.

New Scientific results

1. Modeling of the reconstruction from non-Fourier-type holograms by a method based on Monte-Carlo simulation.

I have shown, that the Monte-Carlo algorithm can be used for the numerical investigations of reconstruction. It is known, that the information about the object is distributed along the entire hologram. That is why the simulation of reconstruction can be managed by the consideration of randomly chosen pixels of hologram. It was examined how the reconstruction depends on the parameters of non-Fourier-type holograms. Computational time was reduced by the application of the mentioned random process. [1,7,8]

2. The image quality of the reconstruction is characterized by correlation

Formerly mainly the diffraction efficiency, the SNR and the MSE parameters were used to characterize the reconstruction. I have suggested to qualify the image fidelity by the correlation between the matrices of the object and reconstructed real image. (The correlation is a very informative parameter for the analogy of the two intensity distributions.) The disadvantages of SNR and MSE don't appear if the parameter of correlation is used at different arrangements and pictures at different illumination. [2]

3. Application of the importance sampling algorithm to improve the convergence

In Monte-Carlo simulations the least standard deviation can be reached when the importance sampling algorithm is used to choose the random points (pixels) on the given region. I have used the algorithm in Monte-Carlo simulation to improve the convergence of correlation. The numerical simulations have proved the theoretical expectations. (The improvement of the convergence was not predictable for "noisy" pictures.) [2,10]

4. The application of "double Monte-Carlo method" reducing the computational running time

The reconstruction by the pixels of a non-Fourier-type hologram can be calculated by the Fraunhofer approximation. In this case the diffraction pattern of the pixels had to be added up. The computations can be reduced significantly. A point source was chosen randomly in the region of each pixel. Its spherical wave is taken into account in simulations, instead of the diffraction pattern of the pixel. It was shown by numerical modeling, that there is no significant difference between the double Monte-Carlo algorithm and Fraunhofer

approximation in correlation. That is why the law computational double Monte-Carlo algorithm can replace the Fraunhofer approximation. [2]

5. The application of the developed processes for optimizing kinoform lenses and numerical investigation of focusing short laser pulses

The ultrashort wave pulses are used not only in optical laboratories, but in optical metrology and telecommunication, too. Holographic optical elements can be used as simple and cheap couplers. Short laser pulses are used to be focused by glass lenses and kinofoms. The application of kinoform lenses focusing short light pulses (<1ps) provides an opportunity to avoid the problem of dispersion. I have made numerical investigations to determine the intensity distribution of the light pulse passing the focal plane. The developed method for reconstruction was used to calculate the pulse shape, intensity, etc. The results are presented in 2.3.5.

I have proposed an optimization process – based on iterative Monte-Carlo algorithm – for performing kinoform lenses. [3,9]

6. Estimating formula for the convergence of correlation

I have given a modified definition for the image fidelity. It was necessary to eliminate the errors generated by the quantization and averaging. At first the reconstruction was simulated by considering all the pixels of the hologram. The reconstructed image from the entire hologram was compared with the reconstructed picture of the object calculated by Monte-Carlo algorithm. (In the case of multifocal holographic lenses the difference between the numerical values of the two definitions is not significant.) I have given a new approximating formula for the estimation of the correlation by the use of probability theory and statistics. The results are presented in 2.3.6.

7. Digital holography by two reference beams

Two optical arrangements without any phase shifter were suggested to record digital holograms. It was shown, that the zero order elimination can be achieved by the use of the developed algorithm. [4,5,6]

Applications

The simulation method for modeling the reconstruction of non-Fourier-type holograms – with the optimization algorithm – is useful in planning and construction of holographic optical elements. The results of the numerical investigations to describe the focusing of short laser pulses by phase holographic lens can be significant in optical metrology. The optical arrangement and algorithms presented in digital holography can be adopted for some industrial use (3D shape measurement, holographic interferometry, etc.).

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