Conference Paper

Coefficients Quantization at Off-axis Digital Hologram Wavelet Compression

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Abstract

Digital holographic information is compressed for storage of 2D- or 3D-objects amplitude and phase distributions, fast transmission, analyzing and displaying of these data. In this paper features of application of wavelet transforms for off-axis digital holograms compression are considered. The combined technique based on zero and twin orders elimination, wavelet compression of the amplitude and phase components of obtained Fourier spectrum and further additional compression of wavelet coefficients by thresholding and quantization is analyzed. Numerical experiments on reconstruction of images from the compressed holograms are performed. The comparative analysis of applicability of various wavelets and additional quantization of coefficients is performed. Obtained results demonstrate possibility of 180 and more times compression using iterative and noniterative methods of coefficients quantization and threshold zeroing less 80% of wavelet coefficients.

Keywords: digital holography, hologram compression, wavelets, quantization, thresholding, digital image processing.

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1. Introduction

For increase of digital holograms transfer speed and for decrease of the memory size demanded for its storage, digital holograms can be compressed. For compression of digital and computer-synthesized holograms, various types of compression methods are used [1-4], for example scanning methods [5] and generative approaches [6] are used. In the general case they can be divided into several groups:

- based on standards of image and video compression (JPEG, MPEG-4, etc.) [7-8],
- iterative and noniterative scalar and vector methods of quantization [9-11],

- based on wavelet transforms [12-19], including cosine transform [14-15], fresnelet [16] and others.

Lossless compression can be also used as additional techniques. However if file have a significant amount of gradations, these methods do not give considerable results [10, 20-22].

Majority of papers devoted to compression based on wavelet transforms are aimed to the estimation of achieved compression ratios values. In a number of papers (such as [17]) results of comparison of several wavelet transforms were given. Specifically in paper [17] comparison of Gabor wavelet and fresnelet compression is considered. However results of comparison of other wavelets, despite its huge quantity were not presented. In [2] compression of holograms based on wavelet transforms with additional compression of wavelet coefficients was given. Reconstructed images after Haar wavelet compression were shown. Uniform quantization of coefficients was used, but other quantization methods were not applied. The most widespread methods of compression of digital holograms based on holograms quantization, holograms wavelet transforms, and also standard images compression methods are considered and analyzed in [3]. However results of reconstruction quality comparison were not given. In the paper [23] cases of application of several wavelets in compressive digital holography are considered in detail, but there is no assessment of methods of direct truncating of wavelet coefficients.

For the case of off-axis [24-25] digital holograms, frequency filtering of twin and zero orders [26-27] can be applied too. In case of compression of off-axis holograms significant compression ratios can be achieved through saving only informative diffraction order. Thus it is possible to reduce requirements for necessary memory size and in some cases also improve quality of image reconstructed from compressed by described filtering hologram. Application of this filtering method allows to reduce the useful holographic data size considerably. Currently compression of off-axis digital holograms is used for the tasks of microscopy, metrology, fast 3D-object reconstruction, interferometry, and etc. [7-8, 28-30].

In the paper [31] results of compression of off-axis holograms by combined method based on frequency filtering of undesirable diffraction orders (twin and zero orders), separation of amplitude and phase components of Fourier spectrum of filtered hologram, wavelet transform of amplitude and phase components, threshold zeroing and quantization of wavelet coefficients as additional compression of wavelet coefficients in case of low threshold values (60-70%) are presented. Aim of this paper is further estimation of quality of reconstructed images from the compressed off-axis holograms. Frequency filtering, different wavelets and additional processing of wavelet coefficients are also applied. As methods of additional compression threshold zeroing of 80% wavelet coefficients and its quantization are applied. Results of reconstructed image quality are given.

2. Methods

2.1. Used technique

For compression of off-axis digital holograms in paper the combined methods are offered. These combined methods consist of the following stages:

- frequency filtering of undesirable diffraction orders (twin and zero orders),
- separation of amplitude and phase of Fourier spectrum of filtered hologram,
- wavelet transform of obtained amplitude and phase components,
- additional compression of wavelet coefficients by quantization and thresholding [31].

The most popular methods of additional compression are used: threshold zeroing and different iterative and noniterative quantization methods. Earlier in literature only part of the specified stages was considered [2-3, 23] but for the tasks of compression of inline holograms. Since 2002 in the majority of papers separation of Fourier spectrum of filtered hologram to real and imaginary components is used (for example, [1, 9]). However in this paper we used separation of amplitude and phase components of Fourier spectrum of filtered hologram as in the papers of 1960-1980-s, though it can be less optimum.

2.2. Use of wavelets

For the analysis of wavelet stages of compression 14 methods on the basis of various transforms are realized: in particular Haar, Daubeshi, Meyer, biorthogonal, reverse biorthogonal wavelets, coiflet and symlet with different parameters. Methods of additional compression of wavelet coefficients are used also: in particular its threshold processing and iterative and noniterative quantization.

Examples of application of wavelet transform (in case of 3-level wavelet transform) to standard image and to synthesized digital hologram are shown in Fig. 1. At wavelet decomposition [32] there are approximating coefficients (A) which contain the main components of initial image, and also horizontal (H), vertical (V) and diagonal (D) coefficients of transform which contain information on intermediate values of the initial image. In Fig. 1(a,e) are shown horizontal, vertical and diagonal coefficients for 2 level of wavelet decomposition and all coefficients for 3 level decomposition in high left part of image.

In the case of standard amateur images, wavelet transform compression methods allow to reach high compression ratios with minimum losses of quality [33]. As a result of compression based on wavelet transform decomposition of the initial image on arrays of the approximating coefficients and related coefficients of specification is used. Coefficients of this approximation allow to consider dependences between values of a signal (intensity) in the next pixels. In case of standard images (amateur images) compression is aimed on digital processing of brightness gradients since it is possible to describe it's by a small number of coefficients.

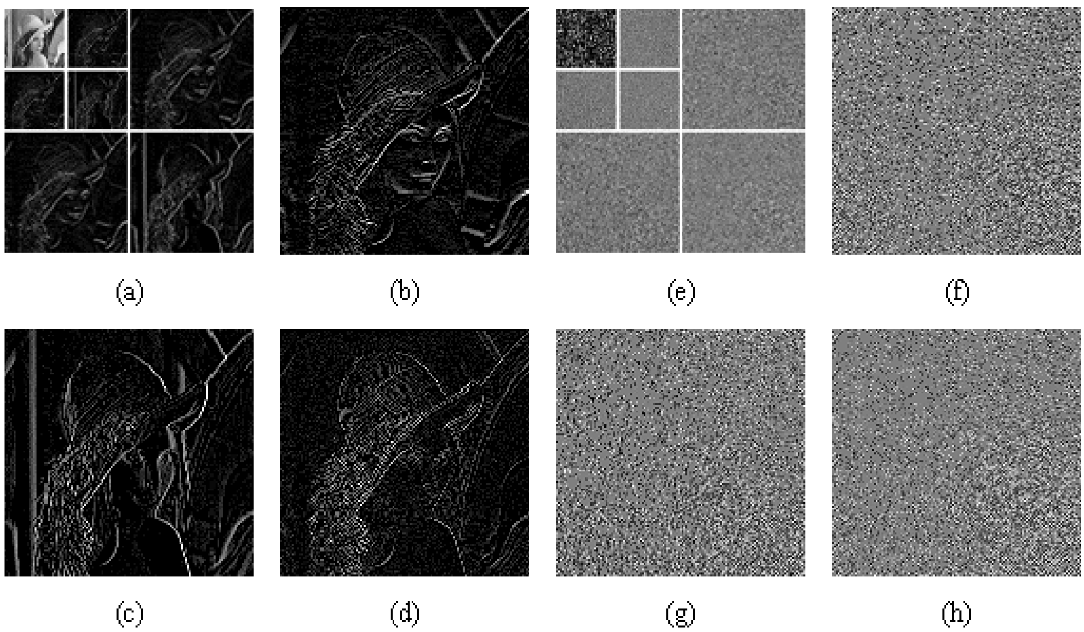

Figure 1: Coefficients of wavelet transform of grayscale image and synthesized digital hologram: horizontal (b, f), vertical (c, g) and diagonal (d, h) ones, same coefficients for 3-level wavelet decomposition (a,e).

However holograms like actually interference patterns with a large number of small details with different brightness are described by large number of the coefficients. There is significant correlation between adjacent pixels in digital images and less correlation in digital holograms, so decomposition of digital images is more effective than decomposition of digital holograms. Thus, in case of compression of digital images by methods based on wavelet transforms much higher compression ratios, than in case of compression of digital holograms, are achieved. In case of compression of digital holograms by such methods, additional thresholding and quantization of wavelet coefficients, and also entropy coding - the subsequent processing of coefficients by "lossless" compression methods can be applied.

2.3. Used holograms and reconstructed images

In the paper two types of holograms were used: the registered optically digital holograms of coin [34] with up to 2048×2048 pixels and also synthesized digital holograms with up to 2048×2048 pixels. In the case of synthesized holograms different binary and grayscale objects with sizes of 64×64, 128×128, 256×256 pixels were used. Conditions of numerical experiments were chosen equivalent to ones that can be implemented at recording of digital off-axis Fresnel holograms. Wavelength of light was equal to 532 nm, hologram pixel size was 9 μm × 9 μm. Distance from the object to the hologram plane ranges from 0.4 to 1.5 m. Object's images were positioned in the left part of full object field. The phase of object field is randomly distributed from 0 to 2π over all pixels. Thus the object radiates diffusely. For reconstruction of images from digital holograms the method of Fresnel diffraction direct calculation can be applied.

In Fig. 2 full object field (2048×2048 pixels) reconstructed from experimentally recorded digital hologram of coin and objects reconstructed from this hologram before and after filtering are given. In Fig. 3 digital holograms fragments (size of 128×128 pixels) before and after filtering are given.

In this paper further analysis of application of the combined methods for off-axis holograms compression is performed. In this analysis various wavelets, various parameters and its combinations for methods of additional compression of wavelet coefficients, such as threshold value, the method of quantization of wavelet coefficients and also the number of bits at quantization are used.

2.4. Estimation of reconstruction quality

As measure of quality of reconstruction, PSNR value [35] was used:

$$PSNR = 20\log_{10}\left(\frac{MAX_f}{\sqrt{MSE}}\right), \qquad (1)$$

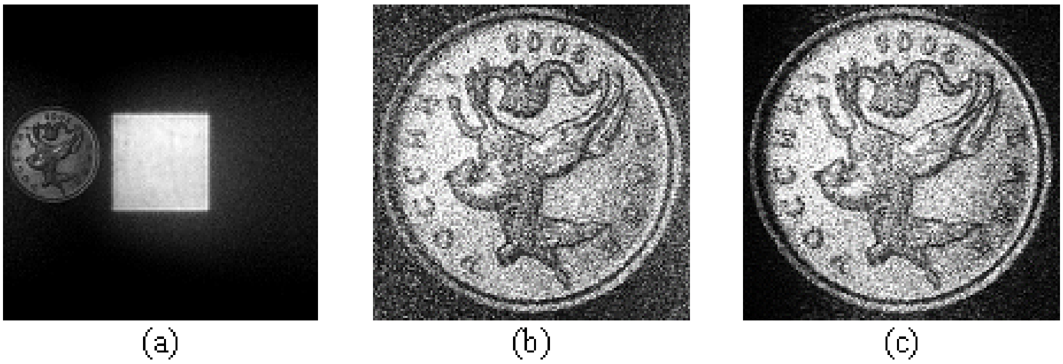

Figure 2: Object field reconstructed from hologram (a), corresponding object image (b), object image after frequency filtering (c).

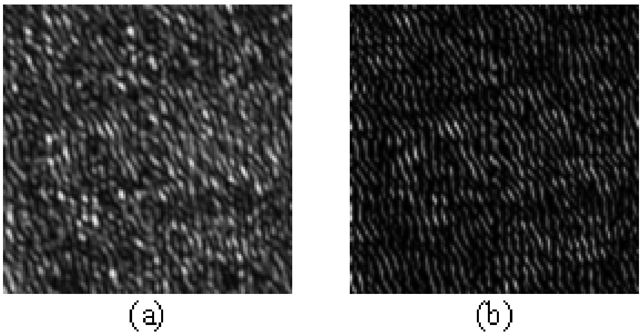

Figure 3: Fragment (128×128 pixels) of original (a) and frequency filtered (b) digital hologram.

where MAX_f is maximum signal value that exists in original image, *MSE* - Mean Squared Error:

$$MSE = \frac{1}{mn}\sum_{\varsigma=0}^{m-1}\sum_{\eta=0}^{n-1}\left\|F_{\zeta,\eta} - G_{\zeta,\eta}\right\|^2, \quad (2)$$

where $F_{\zeta,\eta}$ – original object image; $G_{\zeta,\eta}$ – reconstructed object image; *m*, *n* – quantity of rows and columns of pixels of these images; ζ, η – indexes of rows and columns.

3. Results

Various both iterative, and noniterative quantization methods were applied to additional compression of wavelet coefficients. In Fig. 4 fragment (128×128 pixels) of result of reconstruction of the compressed wavelet coefficients in the hologram plane are presented. This distribution is obtained after:

- reverse wavelet transform of compressed wavelet coefficients of amplitude and phase holograms components,
- consolidation of amplitude and phase hologram components in Fourier domain,
- reverse Fourier transform.

In Fig. 4 fragments of field in the hologram plane without additional compression of coefficients (a), with threshold zeroing of 80% wavelet coefficients without quantization (b) and 80% thresholding and quantization of wavelet coefficients for 3 (c) and 6 (d) bits are shown.

Several popular methods of quantization are applied for compression of wavelet coefficients of the amplitude and phase components of Fourier spectrum of holograms. Example of obtained dependence is shown in Fig. 5 in case of zeroing of 80% of coefficients. Phase was compressed by 3 methods, amplitude was compressed by the same methods, as phase in 1-3 cases. In 4-5 cases was used logarithmic k-means and uniform quantization for amplitude, uniform and nonuniform logarithmic quantization for phase.

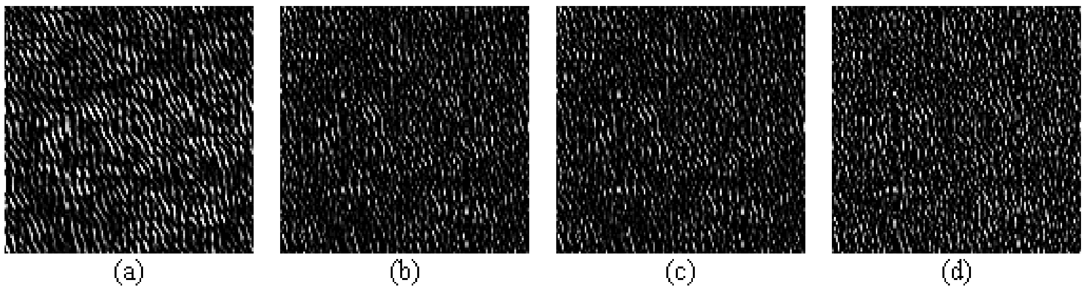

Figure 4: Fragments (128×128 pixels) of result of reconstruction of the compressed wavelet coefficients in the hologram plane after reverse wavelet transform of compressed wavelet coefficients of amplitude and phase holograms components, its consolidation in Fourier domain and reverse Fourier transform in cases without additional compression of coefficients (a), threshold zeroing of 80% wavelet coefficients without quantization (b), 80% thresholding and quantization of wavelet coefficients for 3 (c) and 6 (d) bits.

The best methods for compression of wavelet coefficients of phase component are vector ones, such as dynamic kernels (or k-means [36]) and method of uniform quantization in case of more than 4 bits. Method of k-means clustering allows more accurately quantize the amplitude signals than the simple scalar ones. The worst results are achieved in case of using logarithmic k-means clustering for both components of Fourier spectrum of hologram. In case of quantization for 3 bits and less the worst results are obtained by using also k-means method with logarithmic transformation, simple k-means clustering and combination of k-means method with logarithmic transformation for phase component and uniform quantization for the amplitude one. The best results for 4 bits and more are achieved in case of using k-means clustering and combination of k-means method with logarithmic transformation for phase component and nonuniform quantization for the amplitude one.

In Fig. 6 results of reconstruction of experimentally registered [34] digital holograms, compressed using Haar wavelet are presented. 80% of coefficients are nullified on

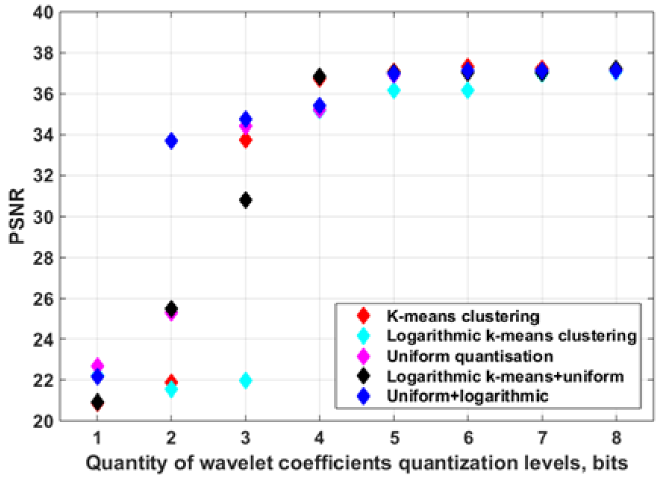

Figure 5: Quality of reconstructed wavelets versus 3-level wavelet decomposition in case of different wavelet coefficient gradations. Phase of filtered hologram's Fourier spectrum was compressed by 3 methods; amplitude was compressed by the same methods, as phase in 1-3 cases. In 4-5 cases was used logarithmic k-means and uniform quantization for amplitude, uniform and nonuniform logarithmic quantization for phase.

threshold and in addition compressed by noniterative (uniform quantization on the level, Fig. 6b,d) and iterative (method of dynamic kernels, Fig. 6a, c) methods of quantization. The obtained data are compressed in 140 (a, b) and in 73 (c, d) times.

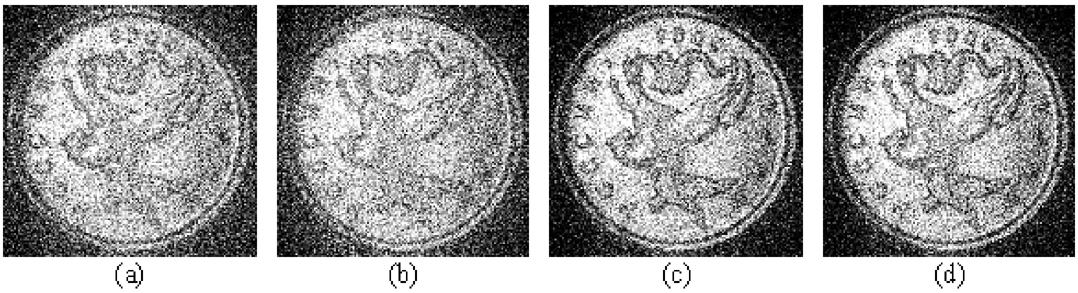

Figure 6: Reconstructed object from the hologram compressed by wavelet Haar with iterative (a,c) and noniterative (b,d) quantization to 3 (a,b) and 6 (c,d) bits in case of threshold zeroing of 80% wavelet coefficients.

4. Discussion

Obtained results demonstrated that in case of compression including filtration of undesirable orders of diffraction, separation of Fourier domain of the hologram into phase and amplitude components, wavelet transform of both components, further threshold zeroing of wavelet coefficients and its quantization, the best quality of reconstruction of the compressed experimentally registered digital holograms is achieved with quantization for high quantity of wavelet quantization levels.

In case of threshold zeroing of 70% or less wavelet coefficients, the best results of quantization are achieved using iterative methods. However in the case of zeroing of 80% wavelet coefficients visually quality of reconstructed images at compression by iterative and noniterative methods almost does not differ. Thus, in this case at quantization to 4 and more bits noniterative methods become more applicable. Noniterative methods considerably surpassing iterative ones on time of processing. From the point of view of the best quality of reconstruction and maximum of compression ratio threshold zeroing of 70-80% wavelet coefficients is also optimum. In case of threshold zeroing of 80% wavelet coefficients quality of reconstructed from compressed hologram image is less than in case of 70% zeroing coefficients but compression ratio is higher. At further increase in quantity of the nullified wavelet coefficients (more than 80% coefficients) quality of reconstructed images begins to get significantly worse.

5. Conclusion

Thus, the combined methods of compression of digital holograms based on frequency filtering and various wavelet processing are analyzed. Experimental comparison of results of reconstruction in cases of using different parameters of the combined method is performed. Numerical experiments were conducted in case of experimentally registered digital holograms with 2048×2048 pixels and synthesized digital holograms with up to 2048×2048 pixels.

Compression of experimentally registered holograms to 190 times (in case of saving of 10% of initial information at filtering of diffraction orders, 2 gradations or 1 bit per pixel and threshold filtering of 80% wavelet coefficients) is obtained. Depending on required quality, time interval of hologram processing and quantity of gradations, it is possible to select suitable methods of quantization for additional compression of wavelet coefficients. For obtaining better compression ratios, lossless algorithms or methods with losses of information can be applied additionally.

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