

Computer processing of electronic speckle pattern interferometry

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Introduction

Holographic method of speckle pattern (SP) registration [1-3] when a photosensitive element is TV camera allows to register an ultrasonic vibration field in real time. As the number of television image pixels do not exceed 500 for one television line, SP holographic resolution is significantly less than conventional one, obtained on holographic photoplates – several or even several thousand lines/mm. Due to so low resolution, SP holography may not be three-dimensional, however, it is quite sufficient for registration interferential bands. To increase the resolution and to improve a registered image quality, at present more and more widely digital TV holography is implemented [4-5].

The purpose of this work is to study digital filters which are most frequently used for improving the quality of obtained interferograms. The acute task is the preparation of the images for processing: filtering of holograms, the separation of the three-dimensional (3D) surface vibrations amplitude level lines from two-dimensional (2D) image and obtaining of three-dimensional vibration image.

The principle of holographic method

The holographic reception of the optic signal $ae^{i\varphi}$, using reference wave $a_0e^{i\varphi_0}$, interfering with a coherent light wave, reflected from the object under investigation, allows to register not only amplitude of light, but also its phase. In this case the total amplitude of the objective and reference waves is

$$a_{\Sigma} = a_1e^{i\varphi_1} + a_0e^{i\varphi_0}, \quad (1)$$

and the intensity:

$$I_{\Sigma} = \left| a_1e^{i\varphi_1} + a_0e^{i\varphi_0} \right|^2 = a_1^2 + a_0^2 + 2a_1a_0 \cos(\varphi_1 - \varphi_0). \quad (2)$$

When the object vibrates, from which is reflected light, the difference of phases $(\varphi_1 - \varphi_2)$ is modulated by a harmonic law, while phase shifts, being dependent in the configuration of the investigated object, in an interferogram are coded by a number of lines. From Eq. 2 may be seen that the damping features of the object influence the light amplitude a_1 and the contrast of interferential line [6]:

$$\mu = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \frac{2a_1a_0}{a_1^2 + a_0^2}. \quad (3)$$

From Eq. 3 is seen that the contrast μ is maximal and is equal to unity when $a_1 \rightarrow a_0$. The information about the optical density of the object is encoded in the contrast of interferograms, and in the form of interferential lines about the spatial lay-out of phases delay:

$$\Delta\varphi = \varphi_1 - \varphi_0 = 2\pi(n-1)l/\lambda, \quad (4)$$

where n is the medium refractive index, l is the geometric difference between objective and reference light paths, λ is the wavelength of the light source.

A schematic diagram of a holographic system, designed for the registration of SP interferograms, is presented in Fig. 1 [7]. The surface of the investigated vibrating object 1 is illuminated by a laser diode or by pulse laser light 2, the propagation angle of which $\theta < 10^\circ$. The object surface image by the diaphragm 3 and lens 4 is focused on the TV camera 7 the image surface. The reference beam 6 is summed up with the reflected wave front of the vibrating object 1 by a wedge-shaped summator 5. As the surface of the object 1 vibrates according to $\xi(t) = \xi_0 \sin \omega t$, the average light intensity in time $\tau \gg 2\pi/\omega$ on the TV camera 7 image plane of the sensitive sensor is expressed by [2]:

$$I_{\tau} = I_{atr} + I_{obj} + 2\sqrt{I_{atr}I_{obj}} \cos \Delta\varphi, \quad (5)$$

where I_{atr} and I_{obj} are the intensities of the reference and object light flows.

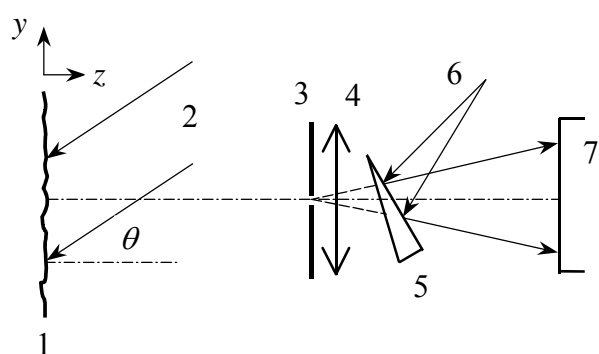


Fig. 1. Schematic diagram of SP holographic interferometer: 1 – object vibrating surface, 2 – coherent light beam, 3 – diaphragm, 4 – focusing lens, 5 – wedge-shaped summator of light beams, 6 – reference coherent light beam, 7 – digital camera (CCD)

When the surface of the object 1 is deformed, the phase $\Delta\varphi$ changes and light intensity is [4]

$$I_{\tau} = I_{atr} + I_{obj} + 2\sqrt{I_{atr}I_{obj}} \cos(\Delta\varphi + \Delta). \quad (6)$$

Thus, when the amplitude of mechanical vibrations ξ_0 changes, also changes the image contrast of the mechanical vibrations distribution, taking minimum values when the values of the vibration amplitude are [2].

$$\xi_{0n} = \frac{n\lambda_0}{4}, n = 1, 2, 3, \dots \quad (7)$$

The interpretation of the vibrating surfaces holographic interferograms and its convenient representation is one of the up-to-date problems of laser registration of vibrating surfaces. The speckle nature of interferograms has a rather great influence upon the accuracy of obtained results, because it is not possible to determine the boundaries of the areas with different vibration phases. To reduce the speckling influence digital processing filters may be used [8, 9].

The essence of the digital filtering is to filter noise signals from holographic interferogram obtained at the CCD output in the form of a data array [10]. Digital filtering is a mean of image processing, which allows changing in some way the intensities of available image pixels. The changing extent of each pixel depends not only upon the pixel to be changed, but also on adjacent pixel intensity. Fig. 2 illustrates the principle of interferential image filtering, “many → one”.

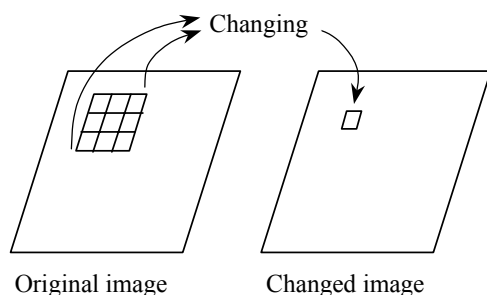


Fig. 2. Image filtering principle “many → one”

There are two types of digital filters: frequency and spatial ones. For frequency filtering there used Fourier transformation, while for spatial filters – “mask”. The spatial filters are divided into the following types:

- low pass filters;
- high pass filters (fringes exposure; may be increased noise level in them);
- band pass filters (equalisation retaining contours; they filter speckling);
- contrast filters (equalisation retaining contours; they filter speckling).

Low pass filters are used to equalise image pixel intensity, however, at an expense of accuracy. Meanwhile, high pass filters allow to expose the contours, but at the same time the noise level may be increased. In order to remove the periodic noise band pass filters are used. To filter image speckling, contrast filters may be successfully used, by which it is possible to equalise image pixel intensity not losing contours.

In order to retain a high spatial frequency information, to perform filtering process according to a certain algorithm is not enough. Additionally, into the filtration

process should be inserted a certain “intelligence” [8]. When filtering a multiplicative noise by local statistic filters, image intensity may be expressed as a product:

$$I_{image} = I_{sign} \cdot I_{noise} \quad (8)$$

We shall discuss most often used digital filters more duple.

Median filter [8] is a low pass value equalising spatial filter. It is particularly effective when the noise model is formed of many speckles and distinct fringes. Median filter is not linear. By this filter each pixel value is changed by the middle value of grey scale, which is obtained as the average of adjacent pixels values.

Fig. 3 shows filtration by a median filter, having chosen 5x5 window. The image values area on the left-hand side is not changed. The real value of the window centre pixel is 3, while the average weights of the adjacent pixels are 4. Therefore when filtering by median filter the real value 3 is changed by the obtained med value 4.

Median filter algorithm:

1. Filter window is centred with respect to a chosen pixel.
2. Group all values in the window.
3. Calculate the average of these values.
4. Change the previous value of the pixel into the calculated average value.
5. Go to the starting position. Repeat so long until the whole image has been processed.
6. In order to obtain a better quality, sometimes one should filter several times.

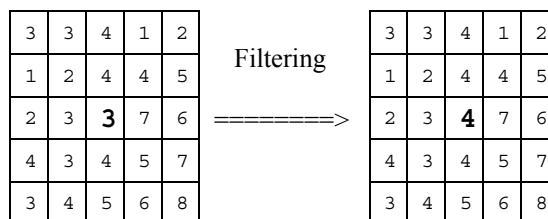


Fig. 3. An example of median filtering

Frost filter is a local statistic filter. The parameters of the Frost filter are chosen according to a local (small enough) area statistics around the chosen pixel. When are being filtered similar zones, the Frost filter operates as an averaging filter. Meanwhile, when filtering high contrast areas, it operates as a high pass filter with fast pixel intensity blur in the filter centre. Then similar large areas will be averaged (filtering away a speckled structure) until the fringes of great contrast or other zones still retain their values. The changed value of the Frost filter $y(t)$ is calculated according to.[8]:

$$y(t) = \frac{\sum_i m(t_i)x(t_i)}{\sum_i m(t_i)}, \quad (9)$$

$$m(t) = e^{-Ka^2(t)}, \quad (10)$$

$$a^2 = \frac{s^2}{z^2}, \quad (11)$$

where s^2 is the map non-coincidence, z is the map value, t is the pixel coordinate, $m(t)$ is the weight factor, K is a constant, $x(t)$ is the real value in the point t ; $y(t)$ is the changed value in the point t .

The Frost filter algorithm:

1. Filter window is centred with respect to a chosen pixel.
2. Calculate value $y(t)$.
3. Change the value of the chosen pixel $x(t)$ into the value $y(t)$.
4. Go to the starting position. Repeat until the whole image has been processed.

Gaussian filter [9] is used to “found” an image, thus eliminating noise and reducing distinctness. From this point of view the filter is similar to that of the median filter, but its algorithm is described by the Gaussian distribution curve. One-dimensional Gaussian distribution is expressed as:

$$G(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{x^2}{2\sigma^2}}, \quad (12)$$

where σ is the standard deflection for x coordinate.

Two-dimensional Gaussian distribution is expressed as:

$$G(x, y) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{x^2+y^2}{2\sigma^2}}. \quad (13)$$

Filtration by the two-dimensional Gaussian filter is performed by calculating convolutions. When the image is retained in the form of discrete pixels, prior to the calculation of the convolutions it is necessary to perform a discrete approximation by the Gaussian function.

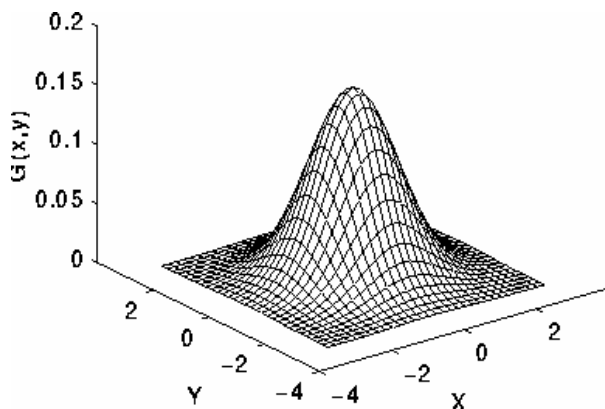


Fig. 4. Two-dimensional the Gaussian distribution

Theoretically the Gaussian function is not zero in all pixels, therefore the convolutions kernel is infinitely large. Practically there is used a finite kernel, limiting oneself to three standard deviation from the mean value, function value, which is outside the kernel limits set to zero. In Fig. 5 is shown an estimated in integer numbers the convolution kernel approximated by the Gaussian law when $\sigma = 1,4$.

Having calculated a suitable kernel once, the Gaussian filtering may be performed using standard convolution methods. The calculation of the convolution may be

2	4	5	4	2
4	9	12	9	4
5	12	15	12	5
4	9	12	9	4
2	4	5	4	2

Fig. 5. Discrete approximation Gaussian function

simplified, because in Eq. 13 x and y components are separated, and the two-dimensional convolution may be replaced by two-dimensional convolutions – in x and y direction.

Vibrations analysis and experiments results

The simplest and cheapest holographic image registration method is photographing, the obtained photograph scanning by a high resolution scanner. By this way in a computer memory is formed a two-dimensional digital array characterising distribution of light in the investigated image.

The initial processing of the interferential images is performed when it is necessary to improve its quality and to reduce a noise. Ideally, the holographic-interferential image of the investigated vibrating object is formed from uninterrupted bright and dark lines. The lines, obtained in a holographic interferogram, correspond to the same amplitude lines. The lines, which are not out of the boundaries of the investigated surface or do not end at the surface perimeter, then those lines are being closed. In reality, interferential lines are distorted due to some dust which covers optical system, also due to external vibrations, microunevenness of the investigated object surface and other effects, thus they do not strictly correspond to the amplitude level lines. Outside light reflections have also some influence, which, summing up with the investigated image, may particularly distort strongly the interferential line. The purpose of the initial processing of the interferential image is to minimise lines deviation from the same amplitude lines of the investigated object surface. Knowing that the lines of the interferential image are uninterrupted and that the image lightness periodically changes according to cosine law, one may use direct transformation of lightness by a spatial filter. For this purpose digital image filters are used which are in standard graphic packets, for example, *Corel Draw*, *Adobe PhotoShop*. We have performed the filtering of the experimental interferential images by digital filters and have chosen from them filters (median, Frost, Gaussian), which best of all fit for the chosen further investigation method for obtaining three-dimensional acoustic vibrations images.

The results of filtering of experimental interferential images, carried out by us are given in Fig. 8. For simplicity, for computer simulation we use symmetric vibration distribution [11], shown in Fig. 6a.

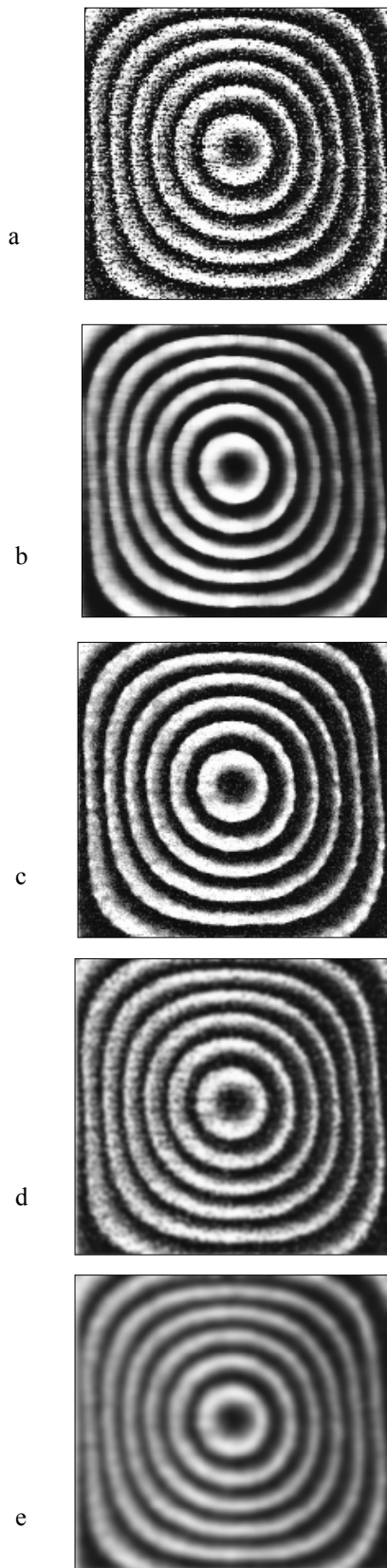


Fig. 6. Holographic interferograms: a – unfiltered, b – filtered by median filter, c – filtered by the Frost filter (10×10 pixels window), d – filtered by the Gaussian filter ($\sigma = 3$), e – filtered by the Gaussian filter ($\sigma = 7$)

In order to estimate the results of digital filtering, given in Fig. 8, *b-e*, not only visually, we extended a matrix series of these interferograms at the central column and graphically showed pixels values functions $F_j(i)$ for all examined cases (Fig. 7). From the cross sections of these interferograms it may be seen that the best filtration lines level is obtained by the Gaussian filter when $\sigma = 7$, but the contrast μ in this case is the lowest.

Carrying out filtering, first of all the interferential lines should be identified. We have limited ourselves by minima lines because their width is smaller, and therefore they represent more exactly the state of level lines. Having performed the initial image processing (filtering by the Gaussian filter), the interferential bands may be automatically recognised by writing a program in *MathCad* or *Pascal* according to the algorithm given in Fig. 8.

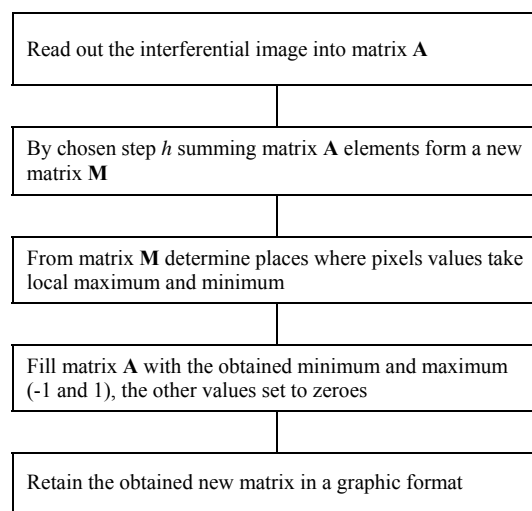


Fig 8. The simplified algorithm of separation of level lines by programmable filter

If the interferential lines are “broken”, then their integrity may be restored manually. Usually this way is used when there have to be processed very complicated interferential images or when the interferogram is not of good quality.

According to this algorithm, having written a programme in *MathCad* language and having used it for image filtering, we obtain a thin lines system of the same level (a holographic interferogram “skeleton”), depicting an acoustic field (Fig. 9).

For further processing of the interferogram “skeleton”, we shall use, as been mentioned above, only closed lines of the dark interferogram part, i. e. lines of minima. The measurement of interferential lines covers the determination of their pixel coordinates and lines numbering, i. e. allocation of a corresponding vibration amplitude level to each line depending on the used holographic diagram. By numbering the lines, for them are being allocated in succession only integer numbers, taking into consideration the tendency of lines changing. To perform this operation, we have formed an algorithm, which is shown in a simple form in Fig. 10.

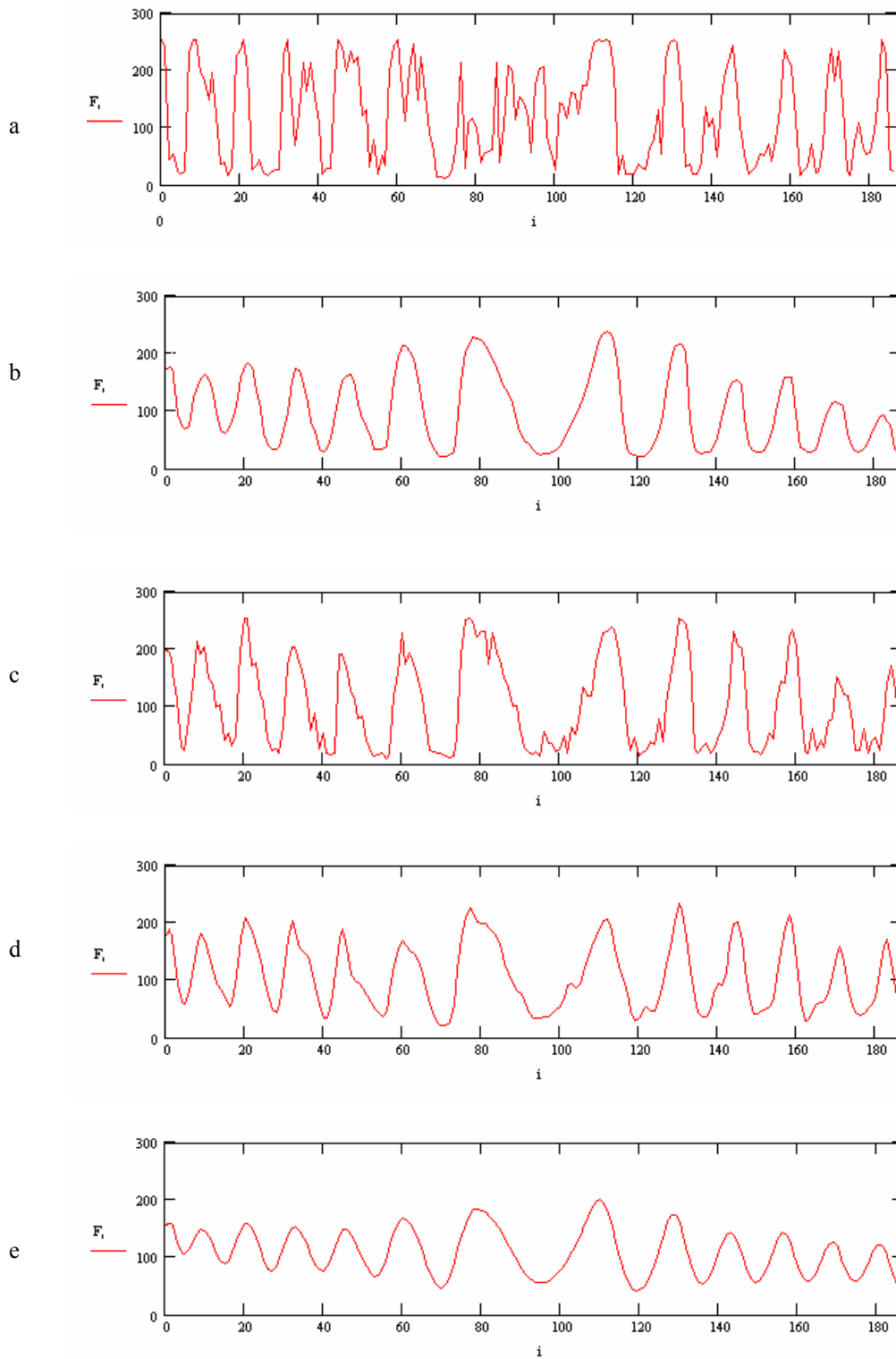


Fig. 7. Interferential values of one line pixels when the interferogram is: a – unfiltered, b – filtered by median filter, c – filtered by the Frost filter, d – filtered by the Gaussian filter ($\sigma=3$); e – filtered by the Gaussian filter ($\sigma=7$)

achieved vibration amplitudes $\xi_0 > \xi_{0\min} \approx \lambda_0/4$ are obtained.

SP holographic interferometry is simple and useful when investigating modes of mechanical vibrations. Although in the digital time averaging TV holography obtained vibration images of spatial distribution are speckled, it is one of the most optimal holographic systems. SP holographic systems are the chipset of all vibrations investigation systems, which allow to process images in real-time. The main disadvantage of this system is speckling of the obtained images, which may be removed by filtration. The image filtration is rather simple, cheap, universal and does not need any special equipment.

The formed processing algorithm allows to process SP holographic interferograms, restructure them and obtain three-dimensional mechanical vibrations images matrixes in a digital form.

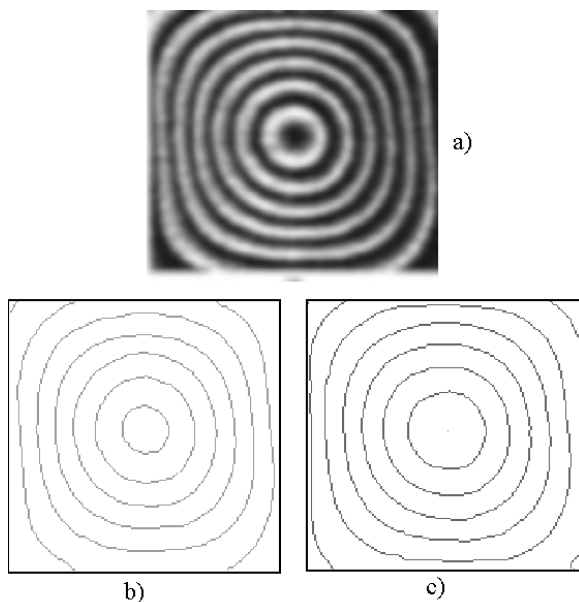


Fig 9. A result of interferogram processing lines programmable separation: *a* – initial image, *b* – having filtered according to maximum (white band), *c* – filtered to minimum (black band)

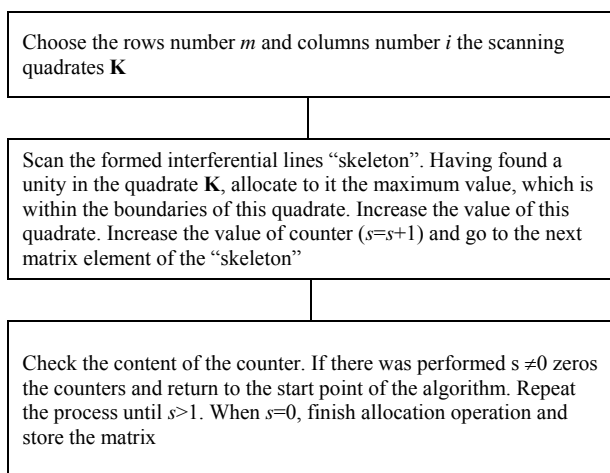


Fig 10. A simplified algorithm of numbering of level lines

By this way $N \times 3$ format array is created, which presents coordinates of N pixels of the three-dimensional surface, showing the investigated interferential image.

The last step of the interferograms processing – from the obtained $N \times 3$ format, having used a standard programmes package, for example, *MathCad 2000*, to form a three-dimensional graphic picture of the acoustic vibrations amplitudes distribution.

Conclusions

Television holographic systems enable to register and visualise mechanical vibrations in real-time in the frequency range limited from below by frames frequency, from above – by a frequency by which in reality are

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Akustinių virpesių hologramų kompiuterinis apdorojimas

Reziumė

Aprašytas grūdėtųjų struktūrų interferogramų apdorojimo metodas, pagrįstas grūdėtųjų struktūrų interferogramų skaitmeniniu vaizdo filtravimu ir apdorojimu interferencinių linijų išskyrimo bei identifikavimo algoritmais. Pritaikius šį metodą grūdėtųjų struktūrų interferogramai, gautas mechaninių vibracijų $N \times 3$ formato masyvas, teikiantis virpesių amplitudės pasiskirstymo trimačio paviršiaus N taškų koordinates.

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