One example of image digital processing of experimental data obtained by the method of photoelasticity

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Abstract. The article is devoted to the digital processing interferograms (isochromatic fringe patterns) obtained by the photoelasticity method. The application to interpretate the isochromatic fringe patterns allows us to automate image processing, gets to avoid the routine and time-consuming work. The features of the developed software package are described in detail by means the problem of stretching plate with two symmetrical edge notches. The application's algorithm includes following main steps: image pre-processing, localization interference fringe, fringe tracing. The application creates a text file containing all the necessary data to further determine the stress-strain state (isochromatic fringe’s number and locus of fringes).

1. Introduction
Photoelasticity method is one of the high-precision experimental methods of solid mechanics. It is a whole-field technique for measuring and visualizing stresses and strains in structures. First of all it is necessary to create samples of transparent material, to conduct a series of tests, to obtain images of the resulting interference patterns, then process these images. The process is quite long, requiring the selection and processing of a large array of points [1–3] to retrieve data using this method. Thus, the need to perform a variety of routines and time-consuming actions, highly skilled personnel, processing of the received experimental data, availability of special equipments, carrying out numerous experiments, the impossibility of obtaining high quality images have led to the fact that this method has been partially supplanted by other, more simple in execution experimental (electronic correlation speckle interferometry, holographic interferometry) [4–7] and computational techniques [8–10]. However, the data obtained by the photoelasticity method are used for calculation analysis in a large number of new published works [11–16]. This is due to the rapid development of computer technology that has occurred at the end of the twentieth century and to the advent of digital images and programs for their processing. It allows us to automate the processing and analysis of obtained experimental data. However, it should be noted that the above publications describe only a few steps with brief instructions for their use.

This work is devoted to a detailed description of the processing procedure of the whole set of experimental information and software that automates time-consuming processing of images.

The photoelasticity method (polarization-optical method) is used for determining internal stresses in transparent bodies, which are believed to be isotropic in the non-stressed state.
It allows us to determine the stress and strain distributions [1–3]. Photoelasticity method is based on the fact that isotropic transparent materials under loads become optically anisotropic. The experimental data obtained as a result of photoelasticity method are used to calculate the principal stresses difference at model points according to Wertheim’s law [3].

\[
\sigma_1 - \sigma_2 = \frac{N f_\sigma}{h},
\]

where \(\sigma_1, \sigma_2\) are principal stresses, \(N\) is order of the isochromatic fringe, \(f_\sigma\) is the optical material constant determined during calibration procedure, \(h\) is thickness of the test sample. Thus, it is necessary to know the coordinates of each experimental point and the order of the isochromatic fringe. Use of the method is expedient and justified for the boundary value problems of fracture mechanics. The obtained data allow us to determine the fracture mechanics parameters, such as stress intensity coefficients \(K_I, K_{II}\), and \(T\)-stresses, and also to find the higher order approximations coefficients of multi-parameter stress asymptotic expansions at the crack tip [13–16].

Thus, to precisely determine the fracture mechanics parameters the digital image processing is required.

2. Image preprocessing
Before processing it is necessary to digitize the images. The image is a rectangular matrix with elements describing the brightness of one or more colors recorded by the camera. Color image as the rule is presented as a mixture of red, blue and green colors (RGB format). The human eye perceives the brightness of these colors differently. As we are only interested in the intensity of a pixel, it is necessary to lead the image to the halftone (black-and-white) view (figure 1) by applying to each pixel (2)

\[
Y = 0.299R + 0.587G + 0.114B,
\]
where $R$, $G$, $B$ are respectively intensity of red, green and blue point images (integers from the range 0–255), $Y$ is total illumination intensity of the image point.

For various reasons the resulting digital image may contain artifacts, which should not be there (the bubbles of the material, from which the experimental sample is made, dust or dirt on the camera lens, defects of the photosensitive matrix). In order to get rid of them different filters can be used. A lot of image filters are based on convolution methods where the kernel plays a central role. Depending on the type of kernel, different effects on original image can be achieved. The smoothing filters are convenient to improve the interference images (Gauss filter, median filter, etc.) [17–19].

The Gauss filter averages the value of the current pixel basing on the values in the neighborhood, but the influence of surrounding pixels decreases with distance from the center.
of the kernel. The Gauss filter’s kernel is calculated from the normal distribution law

\[
K_{i,j}(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{x^2}{2\sigma^2}},
\]

(3)

here indexes \(i, j\) change in the range \([0, 2n]\) for the kernel \(K\) of dimension \(2n + 1\), \(\sigma\) is radius of smoothing neighborhood, \(x = \sqrt{(i - n)^2 + (j - n)^2}\) is the distance from the center of the neighborhood. The filter is applied to each point of the image.

In contradistinction to the Gauss filter the matrix size of a median filter affects only the amount of selected pixels. The algorithm of this filter is the following: matrix window is placed on the current pixel, then all the pixels covered by the kernel are selected and sorted, and average value of the sorted array takes the new value of the current pixel. This filter allows us to get rid of small defects of the image, without disturbing the overall picture.

The Gauss filter smooths the image (figure 2) and (figure 3), and the median gets rid of minor defects and emissions that interfere with further digital processing images (figure 4). Therefore, it is reasonable to use both filters together (figure 5).

3. Fringe localization

The next step after the image preprocessing is fringe localization. To construct the skeleton of isochromatic fringes one can use non-convoluted filter. The matrix with criterion of belonging of pixel to a strip is defined. It uses a 5x5 pixel mask

\[
K = \begin{pmatrix}
    k_{-2,-2} & k_{-2,-1} & k_{-2,0} & k_{-2,1} & k_{-2,2} \\
    k_{-1,-2} & k_{-1,-1} & k_{-1,0} & k_{-1,1} & k_{-1,2} \\
    k_{0,-2} & k_{0,-1} & k_{0,0} & k_{0,1} & k_{0,2} \\
    k_{1,-2} & k_{1,-1} & k_{1,0} & k_{1,1} & k_{1,2} \\
    k_{2,-2} & k_{2,-1} & k_{2,0} & k_{2,1} & k_{2,2}
\end{pmatrix},
\]

(4)

that moves across the image in different directions (up, down, and diagonally). Four types

![Scanning masks.](image)

of masks move across the image in different directions (up, down, diagonally). So there are four pairwise orthogonal matrices and to obtain the complete image it is necessary to logically add up the results of perpendicular scan directions (figure 6).

Each individual scan direction finds the local minimum illumination level. The criterion of minimum illuminance is the following

\[
\begin{align*}
(k_{2,2} + k_{1,2} + k_{2,1}) & > (k_{1,-1} + k_{0,0} + k_{-1,1}) < (k_{-2,-2} + k_{-1,-2} + k_{-2,-1}), \\
(k_{2,-2} + k_{1,-2} + k_{2,-1}) & > (k_{-1,-1} + k_{0,0} + k_{1,1}) < (k_{-2,2} + k_{-1,2} + k_{-2,1}), \\
(k_{2,-1} + k_{2,0} + k_{2,1}) & > (k_{0,-1} + k_{0,0} + k_{0,1}) < (k_{-2,-1} + k_{-2,0} + k_{-2,1}), \\
(k_{-1,-2} + k_{0,-2} + k_{1,-2}) & > (k_{-1,0} + k_{0,0} + k_{1,0}) < (k_{-1,2} + k_{0,2} + k_{1,2}).
\end{align*}
\]

(5)
Figure 7. The algorithm to obtain the fringe skeleton.

The skeletons obtained by diagonal and horizontal scanning are added to separate images, and then multiplied using the logical operation "and". Logical multiplication by each other gives the final picture of the localization of isochromatic fringes with a minimum of noise. Thus, in the final skeleton there are only those points that are recognized in both cases (figure 7).

4. Alternative localization algorithm
In the alternative algorithm we use two sets of masks (figure 8) and (figure 9) for localization of interference bands. An array of five consecutive point values through which the scan vector passes is built. Suppose that $P$ is a matrix of the illuminance values covered by the mask, which is represented in the form (4). The estimated pixel is at $P_{0,0}$. Then for the first mask (figure 8) scan vector coefficients will be $[P_{0,-2}, P_{0,-1}, P_{0,0}, P_{0,1}, P_{0,2}]$. The scan vector only partially passes some pixels (marked circles at (figure 9), so per intensity the average illumination value of nearby

Figure 8. Direct scanning.
Figure 9. Additional scanning.

pixels is taken. For the second mask array the coefficients of the scanning vector are

\[
\left[ P_{1,-2} , \frac{P_{1,-1} + P_{0,-1}}{2} , P_{0,0} , \frac{P_{0,1} - P_{1,1}}{2} , P_{-1,2} \right].
\]

The criterion of minimum illumination is the fulfillment of at least two conditions

\[
(v_0 > v_1 \land v_1 > v_2 \land v_2 < v_3 \land v_3 < v_4),
\]

\[
(v_0 > v_1 \land v_1 > v_2 \land v_2 = v_3 \land v_3 < v_4),
\]

\[
(v_0 > v_1 \land v_1 = v_2 \land v_2 < v_3 \land v_3 < v_4),
\]

\[
(v_0 > v_1 \land v_1 = v_2 \land v_2 = v_3 \land v_3 < v_4),
\]

\[
(v_0 = v_1 \land v_1 = v_2 \land v_2 = v_3 \land v_3 = v_4).
\]

(6)

5. Fringe tracing

The data obtained after the initial localization of the interference fringes are not accurate enough. Fringes have different width, it is not known whether the two randomly taken pixels belong to isochromatic fringe [20]. Thus, it is necessary to split the pixels into separate groups by suitable criterion [21]. This procedure is called tracing.

Let’s consider one of the ways to divide an image into groups of pixels belonging to a closed area. It will be, at best in this case, a separate interference fringe or part of it.

For convenience, we assume that there is a function \(g(x, y)\), which returns a Boolean value of false if a point with coordinates \((x, y)\) does not belong to any fringe. Otherwise the function returns a value equal to the illumination level of the pixel with coordinates \((x, y)\). The trace algorithm (figure 10) consists of the following steps:

1) the search starts from any point of the image, but since all of them have the same value, it is most convenient to start from the point with coordinates \((0, 0)\);

2) iteration procedure begins over unverified pixels. If the pixel belongs to a fringe \((g(x, y) \neq false)\) and is not marked as used, then it is new fringe. We begin to bypass the points of this fringe: collect all the points of the isochromatic fringe, marking all checked pixels to avoid infinite loop;

3) if there are still unverified pixels go to step 2. The scheme of the wave fringe tracing algorithm is shown in (figure 10). As noted earlier, the bypass starts from the upper left corner (the direction of the bypass is carried out from left to right, from top to bottom). When a pixel belonging to the fringe is found, the launch of a spherical wave is initiated with the center in the found pixel point [22]. Tracking the front of its spread, we find other points belonging to the fringe (figure 10).
6. Application of interference fringes localization in the image to the problem of stretching plate with two symmetrical edge notches

As a part of this work the software application for processing of fringe patterns based on above algorithms was developed. The application algorithm consists of several stages:

- select an image file to process (figure 11);
- automatic processing of the uploaded image. This step includes the following steps:
  - image preprocessing (the image is improved by using filters);
  - primary localization of interference fringes (getting approximate location of isochromatic fringe);
– fringe tracing (getting a set of arrays of points belonging to non-intersecting fringe); After starting and running the program the layer containing the image skeleton is superimposed on top of this picture (figure 12).

- the fringe ordering. This step is quite time-consuming for automatic processing, as it generally requires consideration of the sequence of images obtained by sequentially increasing the load applied to the sample. As the load increases the fringes gradually move away from the tips of the cracks. Therefore, the fringe ordering is realised as a manual process. The algorithm for specifying the fringe order is as follows:
  - select with the mouse the pieces of the desired fringe;
  - click the "SaveAsFringeUnion";
  - in the pop-up window, enter the strip number, click "Ok";

Sets of points belonging to one isochrome fringe are manually selected and is assigned a specific number (figure 13).

- uploading the result to a text file. The list of the point coordinates of the marked interference fringes will be uploaded to the text file. Points are unloaded as triples of the form:
  \( \{ N, x_1, x_2 \} \),

where \( N \) is fringe order, \( x_1, x_2 \) are pixel coordinates of the point belonging to this isochromatic fringe. As a result the program creates a text file containing a user-defined number of points of the isochromatic pattern (figure 14) and (figure 15).

The obtained experimental data have the most convenient format for defining fracture mechanics parameters: stress intensity factors, T-stresses and coefficients of higher order approximations of the M. Williams series expansions of the stress field.

7. Conclusions
The paper describes algorithms for processing the results of optoelectronic measurements obtained by the photoelasticity method. It should be noted that numerical methods used for
processing interference patterns can also be used to process images received by other methods such as, for example, electronic correlation speckle interferometry, holographic interferometry.

The developed application based on the considered algorithms allows to determine the coordinates of the points lying on the isochromatic fringes for further processing of these...
Figure 15. Text file with results of digital image processing.

coordinates in any other programs.

The application was written in JavaScript using ES2015/ES6 syntax, the application interface was developed with using frameworks Bootstrap and AngularJS.

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