Real-time study of high-cycle fatigue damage using the averaged speckle dynamics

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Summary. The theory of the method permitting a study of damage accumulation in high-cycle fatigue of reflecting and transparent objects using the time-averaged speckle images is briefly discussed. The formulas that relate the relative displacement vector of the scattering centres to the time-average intensity and the temporal autocorrelation function of this intensity at some observation point are presented. A technique identifying the component of the relative displacement vector as local plastic deformations emerge during fatigue testing is discussed. The issue of real-time recording and processing of the speckle images using the conventional personal computers and special-purpose video systems with function-oriented processors based on homogenous computing environment is discussed. Processors with homogenous architecture allow assurance of the highest possible image processing performance within the order of 10-teraflops/s. The specimens, the optical system, the equipment for fatigue testing, the USB camera and the software used in high-cycle fatigue experiments are discussed. The possibilities and prospects for application of this technique and equipment in evaluation of the remaining life of some object types are discussed.

1. Introduction

It is known that high-cycle fatigue of the material is the dominant destruction factor of mechanical parts and construction elements [1]. Nevertheless, currently there are no relevant physical models of fatigue failure, and the engineering practice lacks techniques for evaluation of material and construction durability [2, 3]. This situation is to a large extent related to absence of simple, reliable and unambiguously interpreted techniques for studying the fatigue failure without interrupting the cyclic loading process.

Previously, we established the dependences relating the time-average radiation intensity and the temporal autocorrelation function at some point of the image plane of the intermittently deformed object with an average value, variance and correlation time of the difference in the plane point displacements in the conjugated plane. It was shown on the metal specimens that if the averaging time is divisible by the cyclic deformation period, then in case of the absence of irreversible processes the
speckle image sections will be invariable, and in micro-and macroscopic surface profile variation image decorrelation will take place.

The objective of this research is studying the possibility of applying the technique for quantitative evaluation of the limiting roughness values, the surface shape of steel as well as the refraction and density indexes of plexiglas. In this case, the time to the crack start should be evaluated by the variation rate of these values.

2. The conditions of the experiment
5x10x55-mm size samples made from Acruma plexiglas were the research targets. To localize the spot of probable fatigue crack initiation, a sharp V-notch 2 mm deep with a 0.25-mm tip radius was made on the specimen. The cyclic tests were performed using an up-to-date high-frequency testing machine MIKROTRON manufactured by the Rumul firm.

A monochrome VIDEOSCAN-415M-USB TV camera with a matrix containing 782´582 8.3x8.3-µm photocells was used in the experiment. The selected TV camera exposure time of 0.5 s corresponded to ≈50 loading cycles. The object was illuminated by a beam emitted by a KLM-H650-40-5 type laser module with the 0.65-µm wavelength and 40-mW capacity.

The formula for calculating the correlation coefficient of two speckle image fragments is:

\[
\eta = \frac{\frac{1}{nm} \sum_{i=0}^{n-1} \sum_{j=0}^{m-1} (A_{ij} - \overline{A})(B_{ij} - \overline{B})}{\left( \frac{1}{nm} \sum_{i=0}^{n-1} \sum_{j=0}^{m-1} (A_{ij} - \overline{A})^2 \right)^{1/2} \left( \frac{1}{nm} \sum_{i=0}^{n-1} \sum_{j=0}^{m-1} (B_{ij} - \overline{B})^2 \right)^{1/2}},
\]

where \( A_{ij} \) is the digital value of the illumination intensity in a \( m \times n \)-pixel size region in real time, \( B_{ij} \) is the digital value of the illumination intensity in the same region at another time point, and \( i \) and \( j \) are the element numbers in the plane of the \( x \)- and \( y \)-axes, respectively.

3. Theory
It is supposed that the speckle pattern varies due to the following three processes:

- slow translational motion of the specimen along the o\( x \)-axis,
- intermittent oscillation of the specimen also along the o\( x \)-axis with a hard-set amplitude and T period,
- random variation of optical wave paths sounding the research target.

According to the selected model, the waves with a random initial phase first pass through the \( 2a_s \)-diameter region of the object with the centre in point \( A \), where \( 2a_s \) is the linear resolution of the lens. Then the waves pass through a small diaphragm near the lens and reach point \( A'/ \) in the object image plane conjugated to point \( A \). We will determine the optical path length for the \( j \)th wave using formula:

\[
u_j = \int_{l_j} [n_j(l) - n_0] dl,
\]

where \( n_j(l) \) –is the distribution of the refraction index in the phase object along the path of the \( j \)th wave, \( l_j \) is the path length of the \( j \)th wave in the object, and \( n_0 \) is the refraction index in the absence of the phase object; the integration is performed along the wave path.

Admitting that all the random values are independent, and the random values of the differences in the wave pair phases are time-correlated, we obtained an expression for time-average radiation intensity \( I \) and temporal autocorrelation function \( R_{1,2}(t_1, t_2) \) of this intensity at an arbitrary observation point \( q \) of the observation plane [4,5]:

\[
R_{1,2}(t_1, t_2) = I_0 N(N - 1)C_0 \cos[(x_1) + (x_2) - (x_1) - (x_2)] \times e^{-\frac{1}{2} \frac{k \Delta x}{\lambda} \frac{k \Delta x}{\lambda} - \frac{1}{2} \frac{k \Delta y}{\lambda} \frac{k \Delta y}{\lambda}},
\]

where \( I_0 \) and \( C_0 \) are constants, \( x = k \mu, k = 2 \pi / \lambda, \mu \) is the difference of the optical wave pair paths average by the \( 2a_s \)-diameter region and time-average, \( \langle x_i \rangle \) and \( \langle x_j \rangle \) are the values of \( x \) average by the
object ensemble (representation ensemble) at time points \( t_1 \) and \( t_2 \), respectively, \( k_{11} \) and \( k_{22} \) are the variance of value \( x \) at time points \( t_1 \) and \( t_2 \), respectively, and \( k_{12} \) is the temporal autocorrelation function of value \( x \).

Values \( \langle \bar{x}_1 \rangle, \langle \bar{x}_2 \rangle, \bar{k}_{11}, \bar{k}_{22}, \bar{k}_{12} \) in formula (3) have the same meaning as \( \langle x_1 \rangle, \langle x_2 \rangle, k_{11}, k_{22}, k_{12} \). But they characterize variation of the optical wave pair paths emerging only in case of a rough surface motion. If the surface roughness is homogeneous, i.e. \( \langle \bar{x}_1 \rangle = \langle \bar{x}_2 \rangle, \bar{k}_{11} = \bar{k}_{22} \) for normed autocorrelation function (3) we obtain that:

\[
\eta(t_1, t_2) = \eta(u_x) \cos[(\langle x_2 \rangle - \langle x_1 \rangle)] \times e^{\frac{1}{2}k_{11} - \frac{1}{2}k_{12} + k_{12}},
\]

\[
\eta = \eta(u_x) = e^{\bar{k}_{11} + \bar{k}_{12}(u_x)}
\]

where \( \eta(u_x) \) is a temporal autocorrelation function corresponding to displacement of a transparent plate in plane \( XY \).

For the reflecting object formula (4) has the same form, but \( \eta(u_x) \) in it is the correlation coefficient in translational motion \( u_x \) of the object:

\[
\eta(u_x) = \frac{2a_x - u_x}{2a_x}
\]

For the reflecting specimen \( x \) can be found using formula:

\[
x = k\Delta u, \Delta u = \Delta \bar{u} (\bar{l}_1 + \bar{l}_2)
\]

where \( \Delta \bar{u} \) is the mean difference in the point displacement vectors located at the edge of the \( 2a_x \)-diameter region, and \( \bar{l}_1 \) and \( \bar{l}_2 \) are unit vectors that determine the illumination and the observation directions respectively.

If a non-stationary process \( x = x(t) \) is characterized by vanishing variances \( k_{11} \) and \( k_2 \), then:

\[
\eta(t_1, t_2) = \cos(x_x).
\]

Next, let the refraction index in the monitored section remain invariable by the specimen thickness \( L \) and its variations occur only in the direction of the specimen length (\( ox \) axis). If the refraction index grade is constant in the section, then, taking (2) into account, instead of (8) we have:

\[
\eta = \cos \left( \frac{2\pi}{\lambda} L \times \Delta n \right)
\]

where \( \Delta n \) is the difference of the refraction indexes at average characteristic distance \( \Delta x \) along the \( ox \) axis. Let us note that \( \Delta x \leq 2a \). Thus, using formula (9), we can determine value \( \Delta n \).

4. Program interface

The data received from the testing machine and the speckle images were processed in real time in the LabVIEW environment using original software.
Figure 1. 1-value $\eta$ distribution display window, 2-window displaying the current speckle image of the object, 3-coordinate of the cursor position on the screen, 4-window for entering the fragment size to divide the image when displaying the distribution of $\eta$ or processing, 5-window for control region coordinate selection, 6-window for entering the frame count between the initial and the current frame in mode 1, 7-button selecting the entire speckle image region as the control and object observation zone, 8-window for presetting the minimum and maximum correlation coefficient values in $\eta$ distribution, 9-call-button of dependence graphs $\eta(N)$, 10-selection of the active experiment number with the window displaying the experiment description, 11-button for data saving every 1,000 cycles, 12-selecting a directory for saving speckle images, 13-button switching over to forceful saving of all the data, 14-selection of the first frame for plotting dependence $\eta(N)$ in the preset sections, 15-window for presetting the coordinates of the section centres, 16-window for section size selection.

5. Special-purpose video system
In our tests we used single-flow software on a conventional personal computer for real-time data processing. For two frames of 782x582 pixels per second with a 10x10 data correlation distribution window it was sufficient. More complicated tasks will call for paralleling and probably special-purpose processors. One of such computing instruments named homogeneous computation environment (HCE) is being created by a team of Russian engineering designers [6].

HCE is special-purpose computation systems consisting of identical processor elements (PE). Each element is configured for performing an arithmetic or a logical function as well as for exchange protocol implementation with the adjacent units. The homogeneity of HCE architecture permits increasing the computational power by a simple increase in the number of the processing elements (scalability). It also permits reaching the highest possible performance with the preset restrictions on the equipment cost, energy consumption and weight, which makes the HCE applicable in real-time systems.
The most complicated task in HCE programming is reflecting of the algorithm to the array of the processors. HCE programming is the process of presetting every PE to performing the relevant processing and transmission operations necessary to reflect the dataflow graph of the objective to the PE grid. The geometric peculiarities of the programming are the necessity to plot the dataflow spread paths in the two-dimensional PE environment.

Processors with the homogeneous architecture allow reaching the highest possible performance of image processing within the order of 10 teraflops/s. Currently, a team of engineers is developing an algorithm of processing correlation images for studying the fatigue process.

![Figure 2. Minitera-2 HCE prototype.](image)

![Figure 3. Streaming correlation computation algorithm.](image)

6. Results and discussion
The procedure of detection and monitoring on a transparent specimen made from plexiglas was performed using two different optical schemes:

- flatwise;
- an angle $q$ to the $x$-axis

First, the object was observed flatwise; value $\eta$ variations near the notch were monitored in real time. As soon as the first variations in the correlation coefficient distribution appeared, testing in this geometry was stopped. Visual examination of the specimen did not detect any presence of a macrocrack. Analysis of the surface profiles recorded by an optical profilometre before and after the testing with the height resolution $\geq 3$ nm showed absence of any surface relief alterations.

The next stage of the experiment consisted in observation of the zone at an angle during the high-cycle test that was conducted to the specimen destruction. As the crack emerged, the irreversible deformation zone size increased by an order and had an area of several square millimetres. Visual observation showed a crack that covered half of the specimen thickness. Analysis of three-dimensional surface profiles near the crack did not detect any variations of roughness or surface profile.

Let us select a system of rectangular coordinates where the point of reference coincides with the notch tip, the $oy$-axis is directed along the notch axis, and the $ox$-axis is parallel to the specimen axis. We obtained the dependence of value $\eta$ on coordinate $x$ for the frames corresponding to the crack formation stage. The dependence was obtained by scanning the specimen image by the $4x4$-pixel region via the centre of optical inhomogeneity formed prior to the crack.

It was found that when coordinate $x$ is vanishing, dependence $\eta \left( x \right)$ decreases from the value close to 1 to the minimum, and then in the inhomogeneity image centre the value of $\eta$ increases to a value close to 1. This peculiarity of dependence $\eta \left( x \right)$ can be explained by formula (4). By symmetry one can suppose that the difference of the optical paths of the space-averaged wave pairs (averaged by $2a_z$-diameter spaces) and the time in the inhomogeneity centre equals zero. Then the cosine in formula (3) will equal 1, and $\eta$ will depend only on the values of vanishing $k_{11}$ and $k_{22}$. So, variation of the environment refraction index at the pre-destruction stage can be regarded as a determined process altering value $\eta$ by the law of cosines.
The limiting value of the refraction index was found using the speckle images recorded before and after the crack start. It was supposed that value $\Delta n$ was equal to the linear dimension of the lens equalling 10 µm. First, the edges of the irreversible process region were determined by the distribution of value $\eta$ in the object image plane. Then a rectangular region from the periphery of the specified region to the crack was selected. The region was split into uniform subregions. It was supposed that grade $dn/dx$ is constant within a small region. Using formula (9), refraction index $n_1$ was found on the border between the first and second parts. The refraction indexes on the edges of the other sections were found in a similar way.

For transition from the refraction index to the density index we used the Lorenz-Lorentz formula. We determined value $n$ beyond the inhomogeneity limits using the polarization optical method, and we defined the density by the specimen volume and mass. Using these data, we determined the specific refractivity of plexiglas. The application of these methods allowed to establish that the maximum relative irreversible density changes occur during the fatigue of plexiglas, not less than $3.9 \times 10^{-3}$. Let us note that the limiting refraction index values measured using the speckle technique and the polarization optical method coincided well.

![Image](image_url)

**Figure 4.** Distribution of value $\eta$ at different stages of the experiment and three-dimensional profiles near the notch.

Strong profile variation as well as the surface form variation caused by the local plastic deformation were recorded on the steel specimens. The limiting roughness value determined by value $\eta$, $R_a=28$ nm ($R_a=25$ nm measured using a WYKO NT-1100 profilometre), the limiting value of surface slope ratio $\gamma$ obtained by value $\eta$, equalled 0.01 (0.088 which was predicted theoretically).

Thus, knowing the limiting values of density variations $\Delta \rho/\rho$, roughness, plastic deformations (by the surface slope ratio) and the variation rates of these parameters make it possible to evaluate the remaining object life to the initiation of the crack growth.

### 7. Conclusion

Irreversible processes occurring in high-cycle fatigue loading conditions were studied in real time on samples with sharp notches made from Acruma plexiglas and those made from steel using the developed speckle technique.

Using the developed technique and the ellipsometry method, we studied the refraction and density index variations in plexiglas and roughness and surface profile variations in steel. It was shown that the limiting value of the relative density variation in plexiglas was $3.9 \times 10^{-3}$, the limit roughness value $R_a=28$ nm, and the limiting variation of the surface slope ratio $\gamma$ in the plastic deformation zone was 0.01.
8. References

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