Measurement of composite material strain using correlation of ultrasonic images

S A Titov$^{1,2}$, V M Levin$^1$, Y S Petronuk$^{1,2}$ and E S Morokov$^1$

$^1$N M Emanuel Institute of Biochemical Physics RAS, Kosygina ul. 4, 119334, Moscow, Russia
$^2$Scientific and Technological Center of Unique Instrumentation of RAS, Butlerova ul. 15, 117342, Moscow, Russia

sergetitov@mail.ru

Abstract. This paper is devoted to the evaluation of composite materials and components using ultrasonic visualization of structural changes caused by the external force. It is proposed to measure the strain of a sample under load using digital correlation of images recorded by a scanning acoustic microscope. An algorithm for processing the spatio-temporal ultrasonic data is developed to measure the longitudinal and transverse strains versus the applied force. The four-layer carbon fiber-reinforced composites with alternating packing of fibers (90/45) are evaluated by the proposed method. The relationships between the strains and the applied force are obtained up to the destruction of the sample. It is shown that the maximal longitudinal and transverse strains achieved for the test sample are 1.2% and 0.3%, respectively.

1. Introduction

Evaluation of new structural materials, such as reinforced composites, and the study of their mechanical properties are important problems in the field of non-destructive testing and technical diagnostics [1]. One of the effective methods for studying the fracture mechanics of reinforced composites and components is acoustic microscopy [2-3]. A scanning acoustic microscope coupled to a testing machine allows one to visualize structural changes in the material caused by the applied force. For an adequate analysis of the data obtained using this experimental approach, it is necessary to know the applied force and the strain of the sample. The use of contact strain sensors in such a setup is not convenient due to a number of technical limitations.

A non-contact method for the strain measurement based on the correlation of optical images is well-accepted nowadays [4]. In this method, the images of local regions of the sample obtained before and after the force application are compared to determine their relative displacement. However, optical images of the surface of composite samples usually have low contrast at high spatial frequencies, which leads to low sensitivity of the method.

To overcome this drawback, it was proposed to use the correlation of images of the composite structure obtained by electron microscopy [5, 6]. Due to the high resolution and contrast of the electron microscopy images, this approach provides high accuracy of the strain measurements. However, its application is rather limited due to the high complexity and cost of the equipment.

In this paper, it is proposed to measure the strain in composite materials by correlation of ultrasonic images of their internal structure. The proposed technique is based on high-frequency ultrasonic
visualization of the structural changes in composite sample caused by the applied force. The recorded ultrasonic data are processed in accordance with the developed algorithm in order to measure the displacement field and evaluate the longitudinal and transverse strains.

2. Experimental setup

Ultrasonic visualization of the composite structure was carried out using a scanning pulsed acoustic microscope (SIAM), combined with a specially developed miniature testing machine (figure 1). The focused immersion ultrasonic transducer 1 was employed in this device. To generate an ultrasonic image the transducer was moved in a raster manner in a plane parallel to the surface of the sample 2. The ultrasonic echo signals received by the transducer were converted into digital form and recorded as a three-dimensional data array \( s(x,y,t) \), where \( x \) and \( y \) are the coordinates of the scan, and \( t \) is time. The operating frequency range of the microscope was 50-100 MHz and the ultrasonic pulse duration was 30-15 ns. Such parameters provided a spatial resolution of 30–70 μm and an ultrasound penetration depth of 1–4 mm for the CFR composites. A more detailed description of the scanning acoustic microscope can be found elsewhere [7].

![Figure 1. Scheme of the experimental setup (a); image of the transducer, and sample holder (b).](image)

The experimental setup produced ultrasonic images of the composite samples under mechanical load. The testing machine combined with the microscope could pull the samples at a given speed with a force \( F \) up to 5000 N. The carbon fiber composite samples consisted of 4 layers with alternating directions of fibers (90/45) were studied in this work. The sizes of the samples were 100×15×0.6 mm.

3. Data processing algorithm

In the proposed method, two ultrasonic spatio-temporal signals \( s_0(x,y,t) \) and \( s_1(x,y,t) \) were recorded for the sample under various mechanical loads to estimate longitudinal and transverse strain components. Usually, the first signal \( s_0 \) was recorded at a low load, which ensured alignment of the sample after installation in the clamps. This signal was used in further processing as a reference signal.

Each of the signals \( s_0 \) and \( s_1 \) was pre-processed after data acquisition. First, compensation of the curvature of the sample surface and its non-parallelism with respect to the scanning plane was carried out. To achieve this, the delays \( \tau_0(x,y) \) and \( \tau_1(x,y) \) of the echo signals reflected from the external boundary of the samples were measured, and signals \( s_0(x,y,t-\tau_0(x,y)) \) and \( s_1(x,y,t-\tau_1(x,y)) \) were calculated by interpolation over the time variable. To reconstruct the quadrature components of the signals and calculate their envelopes, the Hilbert transform \( G(\cdot) \) was performed. Then the acoustic reference image \( r(x,y) \) and current image \( f(x,y) \) were obtained by the detection of the envelope maxima within the time gate \([t_1, t_2] \) as follows:
The resulting images, traditionally called C-scans, show a two-dimensional distribution of acoustic discontinuities located in the selected layer of the sample. The sampling step of 30 μm was chosen comparable with the spatial resolution of the device. The position and size of the time window were set to increase in-plane changing rate of the image intensity. C-scans presented in figure 2 visualize two inner layers of the composite sample with a fiber orientation of ± 45°. The images show numerous oblique stripes formed by the scattering of ultrasound on carbon fibers in the selected layers. Also, in the image taken at a significant load \( F = 1400 \text{ N} \), there are several dark vertical strips produced by the surface cracks in the layers with a fiber orientation of 90°.

**Figure 2.** Ultrasonic images of the sample at \( F = 30 \text{ N} \) (a) and \( F = 1400 \text{ N} \) (b).

At the next processing stage, the total variable displacement of the sample was compensated. Such a displacement inevitably arises in the experimental setup due to deformations of structural elements with increasing load. The value of this shift was determined by the of image correlation method. In the images measured for the reference small load and for the current load, square regions were selected, and the normalized correlation coefficient was found as follows [8]:

\[
\beta(u, v) = \frac{\sum_{x,y} \left[ f(x, y) - f_{u,v} \right] \left[ r(x-u, y-v) - r_a \right]}{\left[ \sum_{x,y} \left[ f(x, y) - f_{u,v} \right]^2 \right] \left[ \sum_{x,y} \left[ r(x-u, y-v) - r_a \right]^2 \right]^{1/2}},
\]

where \( r_a \) is the mean amplitude for the selected part of the reference image, \( f_{u,v} \) is the mean amplitude for the region of the current image whose size coincides with the size of the reference region and which is shifted by \( (u, v) \) with respect to it. The position of the maximum of the calculated coefficient \( \beta(u, v) \) shows the offsets in the \( x \) and \( y \) directions of the current image relative to the reference one. The reference region should be large enough to obtain a consistent estimate of the correlation coefficient; on the other hand, it should be small compared to the entire image.
To determine the total displacement of the sample caused by the force application, square areas of 100×100 and 300×300 pixels were allocated in the middle of the reference and current images, respectively. The result of calculating the correlation coefficient is presented in figure 3. The maximum of the correlation coefficient is shifted from the center by Δu=21 and Δv=−8 samples, which corresponds to real distances of 0.63 mm and 0.24 mm, respectively. The curve β(v) shown in figure 3(b) passes through the maximum of the function β(u,v) for u=221. The maximum value of the correlation coefficient reaches 0.8 at a noise level of 0.2 – 0.3, which indicates a good reliability of the obtained estimate.

![Figure 3. Correlation coefficients β(u,v) (a), and β(v) u=221 (b).](image)

After eliminating the total displacement of the current image relative to the reference image, the lateral displacement field was estimated. To achieve this, the spatial windows with sizes of 60×60 and 80×80 were selected in the reference and current images, respectively. These pairs were uniformly distributed over the surface of the sample at the nodes of 10×10 grid. For each pair of selected windows, the correlation coefficient was calculated, and the displacement field (Δu, Δv) was determined. Then, the components of the displacement dx(x) and dy(y) were calculated as mean values of Δu(x,y) and Δv(x,y) over the variables y and x, respectively.

4. Results and discussion
The obtained relationships dx(x) and dy(y) were approximated by linear functions using the least squares method (figure 4). The calculated proportionality coefficients can be considered as estimates of the longitudinal γx and transverse γy strains of the sample along the corresponding axes. For the load F=1400 N, the longitudinal and transverse strains were found to be γx=0.94% and γy=0.2%, respectively.
The developed method for the strain estimation was tested on carbon fiber samples under a load that increases up to their destruction. The results of measurements of the strains $\gamma_x$ and $\gamma_y$ are presented in figure 5. It was assumed that in the absence of applied force the strains equal to zero. It can be seen that the strain values grow approximately linearly with the load, reaching 1.2% and 0.3%, respectively. The obtained maximal values of strain are in agreement with the published data [9].

5. Conclusion
In this work, it is proposed to measure the strain during mechanical testing of a sample using ultrasonic visualization of structural changes caused by the applied force. The developed signal processing algorithm is based on the detection and quantitative characterization of the displacement field of the composite medium at various loads. It has been experimentally shown that the proposed method can be used to measure the longitudinal and transverse strains of composite materials.

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