Investigation of various criteria for evaluation of aluminum thin foil “smart sensors” images

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Abstract. Various criteria for processing of aluminum foil “smart sensors” images for fatigue evaluation of carbon fiber reinforced polymer (CFRP) were analyzed. There are informative parameters used to assess image quality and surface relief and accordingly to characterize the fatigue damage state of CFRP. The sensitivity of all criteria to distortion influences, particularly, to Gaussian noise, blurring and JPEG compression was investigated. The main purpose of the research is related to the search of informative parameters for fatigue evaluation, which are the least sensitive to different distortions.

1. Introduction
CFRP are widely used in industry to produce structures and machine parts with improved mechanical properties. Moreover, the application of CFRPs in aerospace reduces the costs due to the possibility of production of large-size parts with minimum joints (e.g. the solid CFRP fuselage sections with no fasteners). The structures during operation are mainly loaded cyclically and the fatigue failure may occur. Therefore, the mechanical state of CFRP should be inspected throughout the operation. Recent papers on the subject of non-destructive testing are devoted to the Structural Health Monitoring (SHM) systems, which can provide information as the damage occurs and improve the safety.

One approach [1] of built-in SHM methods is based on optical image registration of aluminum foil (sensor) glued to the investigated structure. Strain-induced relief is formed on the surface of the sensor due to the cyclic deformation and registered via digital camera. Then the relief is analyzed using different parameters to estimate the mechanical state of CFRP.

In order to provide reliable results the informative parameters for image estimation should be unaffected by noise, blurring, illumination irregularities or defects on the captured image. In the previous work [2] the adapted bilateral filtration was used for image processing and the fractal dimension was used as an informative parameter to assess the mechanical state. The aim of the present work is to determine the influence of a) noise; b) blur; and c) compression; on informative parameters used to process the images of aluminum foil sensors during CFRP cyclic tests.

2. Materials and methods
Rectangular flat CFRP specimens with two edge U-shaped notches were tested cyclically using servohydraulic machine UTM Biss-00-201 (the test mode is uniaxial cyclic tension with stress ratio \( R = 0.1 \)). Polycrystalline aluminum foil was glued on the specimen’s surface and then polished. The images of foil were captured during the test by DSLR camera Canon EOS 550D connected with...
microscope lenses. This optical setup provides images with 5184×3456 pixel size (12×8 mm²). The areas of 1024x1024 pixel size were cut from initial images for numerical evaluation.

The illumination scheme used differs with the setups described in literature. In [3] the foil was removed using acetone and then imaged using microscope: the undeformed areas are bright and folds are dark. In [4] the images of foil were captured while the specimen was clamped in grips during the test, however the diffuse lighting provided similar images: bright undeformed areas and dark folds.

In the present work, the illumination scheme includes two light sources: halogen lamp and point LED (Fig. 1). The halogen lamp (background lighting) was mounted in xz-plane at an angle of 45° to the x-axis. The LED used to increase the contrast of deformation folds was located in xz-plane at an angle of 10° to the x-axis. The illumination setup provides dark image at the initial of the cyclic test, because the light reflects from the mirror-polished foil missing the camera lens. Then the relief forms and the light diffusely reflects from folds, thus deformed areas become bright.

In our previous research [4] the metal specimens were tested and aluminum foil was chemically etched. In the present paper the foil was polished in order to obtain mirror surface. This preparation technique improves repeatability and the comparison of different specimens becomes more correct.

Fig. 1. The scheme of specimen illumination and image capturing

Fig. 2 presents the images captured at different number of cycles after the initial of the test. The first image (Fig. 2,a) captured at 100 cycles is homogeneously dark. At N=1600 cycles (Fig. 2,b) the folds are starting to appear. Further cyclic loading to N=6400 is accompanied with the significant growth of deformation relief (Fig. 2,c). The relief continues to rise and, finally, after the N=29,000 (Fig. 2,d) the relief stay practically unchanged. The plot on the Fig. 3 (line 10) is a dependence of the image mean brightness $I_{\text{mean}}$ on the operating cycles.

![Fig. 2. The images of foil. Number of cycles to failure N: a) 100, b) 1600, c) 6400, d) 29000.](image)

The images were analyzed using following informative parameters [5]: MSE (mean square error); H (Shannon entropy); $F_d$ (fractal dimension); $E_{FS}$ (Fourier energy spectrum); PSNR (peak signal-to-noise ratio); UIQ (universal image quality); VSNR (visual signal-to-noise ratio); $S_q$ (white to black pixel ratio). Then the parameters were investigated for the sensitivity to various distortions.

Image blurring. The captured images of aluminum foil were blurred using of the Gaussian filter. Gaussian distribution in N dimensions is calculated as follows [6]:

$$G(x, y) = C \cdot e^{-\frac{x^2 + y^2}{2\sigma^2}},$$  \hspace{1cm} (1)

where $\sigma$ – standard deviation for Gaussian distribution (it defines the degree of blurring), c – scale coefficient. The degree of blurring was varied from 1 to 10.

Gaussian noise. It is a statistical noise, which has a probability density function corresponding to a normal distribution. Probability density function $P$ of Gaussian random variable $z$ is specified as:
\[ P_G(z) = \frac{1}{\sigma_n \sqrt{2\pi}} e^{\frac{(-z-\mu)^2}{2\sigma_n^2}}, \]  

where \( z \) – gray level, \( \mu \) – mean value, \( \sigma_n \) – standard deviation, which defines noise amplitude [7]. Noise level value was taken from the range 0.03-0.3.

**JPEG image compression.** Photo and video cameras are used as detectors of visual information, but the disadvantage is a data compression, which leads to information loss. The aim of this section is to evaluate a dependence of informative parameter values on image compression rate. For this purpose JPEG compression was chosen as one of the most widely used. The XnView was used to compress the images with the following parameters: DKT – slow, smoothing coefficient – 0, discretization (default) – 2x2, 1x1, and 1x1. Compression degree was varied from 10 to 100 with a step of 10 units.

### 3. Materials and methods

**Undistorted images comparison.** In order to compare all informative parameters (quality assessment criteria) they were calculated for initial (without applying any distortion) image series of aluminum foil obtained at different number of operation cycles. All results were normalized and shown on Fig. 3. It is seen, that all parameters have three-stage behavior, but the duration of each stage and dynamic variation range of each parameter are different. The values of the almost all informative parameters within the range of \( N=1 \ 000 \) cycles stay constant. Further (\( N>1 \ 000 \) cycles) the significant increase of following parameters is observed: \( H \) (line 1), \( F_d \) (2), PSNR (5), UIQ (6), VSNR (7), H-MSE (9). For the rest parameters the second stage (where the parameter starts to rise) begins at higher operation cycles. The third stage has the largest duration wherein the most parameters don’t change their values except \( H \) (1), MSE (4), PSNR (5), Sq (8) and H-MSE (9). The Sq value decreases on the third stage, which makes this parameter unsuitable as a criterion for surface relief evaluation. The mean brightness of an image \( (I_{mean}) \) has similar behavior with \( H \), but \( I_{mean} \) has the less dynamic range. Such behavior of brightness related to the illumination setup. Apparently in the other illuminating conditions the mean brightness curve may differ.

![Graph of informative parameters for image quality assessment](image-url)

Fig. 3. Graphs of informative parameters for image quality assessment the quantity of cycles: 1) \( H \); 2) \( F_d \); 3) \( E_{FS} \); 4) MSE; 5) PSNR; 6) UIQ; 7) VSNR; 8) Sq; 9) H-MSE; 10) \( I_{mean} \).

According to a maximum of dynamic range the appropriate criteria are UIQ (\( \Delta UIQ=1.0 \)), PSNR (\( \Delta PSNR=0.8 \)), \( F_d \) (\( \Delta F_d=0.7 \)), \( E_{FS} \) (\( \Delta E_{FS}=0.5 \)), VSNR (\( \Delta VSNR=0.5 \)). From the sensitivity viewpoint (the parameter to be sensitive to the minor changes of relief on the third stage) the following parameters are denoted: \( H \) (1), \( F_d \) (2), \( E_{FS} \) (3), PSNR (5), VSNR (7) and H-MSE (9).

The calculation and the analysis of informative parameters was performed and then the various distortions (Gaussian noise, Gaussian blurring and JPEG compression) were applied to the initial images in order to investigate the criteria’s sensitivity to different influences. Two additional characteristics were calculated for numerical evaluation of distortion degree: root-mean-square error (RMSE – not the same with MSE) as a function of noise, blurring, compression ratio; and correlation coefficient (Kr) between parameter values calculated for initial and distorted images as a function of distortion ratio.
Consequently, the most appropriate parameters should have the minimal RMSE value and the Kr should be as close to 1.

Gaussian blurring. Fig. 4 shows the plots of RMSE and correlation coefficient Kr from blurring rate. For the most of the parameters in the whole range of $\sigma_b$ from 1 to 10 (Fig. 4a) the RMSE is less than $5 \cdot 10^{-3}$, but there are three parameters where RMSE increases: $F_d$ (2), $E_{\text{FS}}$ (3) and $\text{Sq}$ (8). On the other hand, the Kr (Fig. 4b) has the maximum values for $H$ (1), $E_{\text{FS}}$ (3), MSE (4) and H-MSE (9). Kr has a value in a range of 0.8-0.9 for $F_d$ (2), PSNR (5), UIQ (6), VSNR (7). For the $\text{Sq}$ parameter Kr has a dependence of a curve with a maximum at $\sigma_b=6$.

Joint analysis of the two graphs allows us to make following conclusions. The most insensitive to blurring is MSE parameter, which has $K_r=0.975$ in the whole range ($\sigma_b=1-10$) and minimum RMSE value. Then they are $H$ ($K_r=0.96$) and $E_{\text{FS}}$ ($K_r=0.95-0.94$), despite the $E_{\text{FS}}$ is sensitive to blurring according to RMSE. Sufficiently high Kr values have VSNR ($K_r=0.85-0.89$), PSNR ($K_r=0.84$) and UIQ ($K_r=0.8-0.83$) accompanied with the minimal values of RMSE. $F_d$ also have high Kr (0.85-0.81), but with the increase of blurring rate the RMSE for $F_d$ significantly increases. $\text{Sq}$ is the worst criterion where Kr changes within the range from 0.7 to 0.91 (maximum) and RMSE value is the highest. Finally, the H-MSE, based on the calculation of two parameters, has small RMSE and $K_r=0.96$.

Gaussian noise. Fig. 5 shows RMSE and Kr dependencies on the degree of Gaussian noise, applied to the initial images for each informative parameter.

It is seen that four parameters have constant RMSE in analyzed range of noise degree: $H$ (1), $E_{\text{FS}}$ (3), MSE (4), H-MSE (9). While the error increases for $F_d$ (2), PSNR (5), VSNR (7), $\text{Sq}$ (8) and UIQ (6). The similar, but an opposite trend is typical for UIQ (6) and $F_d$ (2) which are shown on graph Kr=f($\sigma_n$). The Kr value of VSNR parameter (7) increases and for PSNR (5) stays unchanged ($K_r=0.85$). The maximum Kr is typical for $H$ (1), $E_{\text{FS}}$ (3), MSE (4) and H-MSE (9).
MSE is the least sensitive to the noise with \( Kr=0.97 \) (RMSE is constant). In addition, the criteria quite insensitive to noise are \( H \) (\( Kr=0.95-0.965 \)), \( E_{FS} \) (\( Kr=0.96-0.955 \)) and less “stable” criteria are \( VSNR \) (\( Kr=0.85-0.94 \)) and \( PSNR \) (\( Kr=0.84-0.86 \)) with low values of RMSE. \( F_d \) and UIQ are characterized by slight decrease of \( Kr \) with the rise of noise level and sufficiently high RMSE. H-MSE is also insensitive to noise: it has small RMSE and high correlation coefficient (\( Kr=0.97 \)).

**JPEG compression.** Fig. 6 presents RMSE and \( Kr \) dependencies on the degree of compression. Fig. 6a illustrates that RMSE changes in a range of \( 10^{-10} \) to \( 10^{-7} \) for \( E_{FS} \) (3) and MSE (4). The other informative parameters in the range of \( K_{comp} \) from 0 to 50 have RMSE=\( 10^{-5} \). With the further increase of compression degree the RMSE rises to 0.01-0.1 for \( H \) (1) and H-MSE (9). After the analysis of \( Kr \) we can conclude that criteria can be divided into two groups: 1) with high \( Kr>0.94 \) – \( H \) (1), \( E_{FS} \) (3), MSE (4) and H-MSE (9); 2) with \( 0.8<Kr<0.87 \) – \( F_d \) (2), PSNR (5), VSNR (7) and \( Sq \) (8). UIQ has a very low \( Kr \approx 0.77 \), therefore it cannot be attributed to any group.

Joint analysis of graphs on Fig. 6 results to a conclusion that the most suitable and preferable criteria for processing of compressed images are MSE and \( E_{FS} \), because the \( Kr \) is higher than for the other criteria (\( Kr=0.975 \) for MSE and \( Kr=0.96 \) for \( E_{FS} \)), moreover RMSE is the least. Criteria \( H \) and H-MSE show the high correlation (\( Kr=0.95-0.94 \)), however the error is the highest. The second group of criteria has almost the same values: \( VSNR \) (\( Kr=0.85-0.87 \)), PSNR (\( Kr=0.84-0.85 \)) and \( F_d \) (\( Kr=0.84 \)), also they are characterized by moderate error. The \( Sq \) parameter is the most sensitive to distortion influences, because it has average values of correlation coefficient \( Kr=0.79-0.84 \) and RMSE in comparison to the other criteria. The plot character of UIQ parameter could be assumed as the most nonlinear (\( Kr=0.77-0.78 \)) from all of them, besides it has average RMSE.

**4. Results discussion**

As a result of the investigation of all informative parameters the most insensitive to different distortions are \( H \), MSE, \( E_{FS} \) and H-MSE. They are recommended for assessing the relief on the aluminum foil during cyclic tests. Fig. 7 presents these parameters with different distortions.

The Shannon entropy \( H \) is practically insensitive to all types of distortions; therefore this criterion is reliable and adequately indicates the changes in deformation relief. The disadvantage is low sensitivity to deformation after \( N=10 \ 000 \) cycles. The MSE and \( E_{FS} \) don’t have such drawback (they can characterize the relief after 10 000 cycles; the upper limit for \( E_{FS} \) is 20 000 cycles, for MSE 45 000 cycles). But they are slightly sensitive to image blurring. So the H-MSE, which combines the advantages of two parameters, is offered. It is reliable like the Shannon entropy \( H \) and changes in wide range of cycles (up to 45 000 cycles). Based on this research the H-MSE can be recommended for practical purposes for estimation of a specimen lifetime during cycling load.

The obtained results (the tests of foil sensors for CFRP fatigue evaluation) should be compared with the results received in our previous works [4] and other authors [1,3,8] (the metals were tested). The investigated objects are steel [4] and aluminum alloys [1,3,8] and their cyclic test was performed within the elastic region (~0.2% of elongation). So the rate of relief formation was slower than the rate obtained...
in the present work (~1.2% of elongation for testing of CFRP). The criteria in mentioned articles are fractal dimension [1,4,8] and the ratio of white and black pixels [3], which made possible to describe the changes on the foil surface in a wide range (up to 80 000 cycles [3]).

The Fractal dimension and the ratio of white and black pixels are not suitable for CFRP fatigue evaluation, because the rate of relief formation is higher than in a case of metallic specimen. Therefore, these parameters have upper limit of ~10 000 cycles after which the fatigue state cannot be assessed. It was a reason for searching of new criteria to be presented in this work. All parameters, used in the present work can be applied for metal testing with the same illumination setup as well.

5. Conclusion
The investigation of information parameters for strain relief assessment of aluminum foil glued to CFRP specimen was performed. The most sensitive parameters to relief formation were determined and tested in a case of different distortions influence: blurring, noise and compression. The most reliable informative parameters are H, MSE, E_{FS} and H-MSE.

It was shown that these parameters are changing insignificantly with rising of distortion degree. The authors suggest using a combined criterion – H-MSE calculated as the mean value of H and MSE. This complex parameter has wide range of applicability and it is “stable” in analyzed region of distortions influences (blurring, noise, compression).

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