МОНИТОРИНГ НА СТРОИТЕЛНИ КОНСТРУКЦИИ ЧРЕЗ ЦИФРОВ КОРЕЛАЦИОНЕН АНАЛИЗ НА ИЗОБРАЖЕНИЯ

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A STRAIN SENSITIVE PATTERN FOR STRUCTURAL HEALTH MONITORING OF CIVIL ENGINEERING STRUCTURES

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Abstract:

In recent decades, various innovative techniques have been developed to monitor large engineering facilities or their responsible parts. One such technique uses Digital Image Correlation (DIC). It allows engineers to monitor the structures remotely and to detect, measure, and track changes of deformation fields of their surfaces with high precision. In the article, we describe briefly a concept for using DIC technique in structural health monitoring, in which the DIC sensor plays an important role. We present a strain sensitivity pattern, synthesized by us numerically, which is suitable for application to the observed surface when multiscale monitoring is required. The quality of this structure has been investigated with the help of a criterion we have introduced. In order to determine the possibilities for its applications, the structure is subjected to computer transformations, simulating plane rotation and uniaxial stretching. The results of the digital experiments prove the applicability of this strain sensitive pattern in monitoring with different scales of the inspected surfaces images.

Keywords:
Structural Health Monitoring, Digital Image Correlation, Strain Sensitivity Pattern

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1. INTRODUCTION

During the first two decades of this century, progress was marked in developing new approaches and methods for Structural Health Monitoring (SHM) of large engineering structures. This progress is based on different branches of applied science - mechanics, electromagnetism, optics, heat engineering, chemistry and others, and imperatively stimulated by computer technology for receiving, processing and storing large data sets. The current need to inspect and monitor the condition of bridges, buildings and other large structures or their responsible parts has imposed SHM as cutting-edge applied researches. This leads to cheaper maintenance of buildings and facilities, lower running costs, improved safety, and early warning of changes in the structures. SHM techniques measure displacements determine the current deformed and stressed state of inspected objects, assess the level of vibration, the presence of cracks or defects [1].

Digital Image Correlation (DIC) [2] is a non-contact digital optical technique that allows civil engineers to monitor structures remotely and with high precision to detect measure and indicate changes in the fields of displacement and deformation of their surfaces. A very successful illustration DIC method application for studying the loadability of large architectural elements such as reinforced concrete frames subjected to static and dynamic loads is presented in [3].The experiments, reported in this work have enabled authors to think about the future use of this method in structural health monitoring of such architectural elements. The deformation of a road restrain system subjected to a quasistatic bending load was investigated by DIC using a computer-generated strain sensitive pattern applied to one of the surfaces of this metal structure in [4]. General concept for a complex, automated Structural Health Monitoring system has been developed in [5]. Such monitoring requires measurement of displacements and deformations fields of the objects surfaces comprising different areas with different levels of sensitivity and accuracy. This in general implies three levels depending on Fields of View (FOV) dimensions:

i. A global sensor that monitors the whole structure or at least a large part of such a structure;
ii. A local sensor used to determine displacement fields in critical areas under surveillance;
iii. Precision sensor for in-plane displacements fields measurement in a small area of observation but with nanometric accuracy.

A prototype of such a system was used to study the behavior of a metallic railway bridge in the course of its operation. In [6] exploration of 3D DIC for SHM for bridge monitoring is reported. Bridge deflections have been measured and non-visible cracks in concrete have been detected.

The publications quoted above reveal that DIC is an effective approach to monitoring large building structures. The implementation of a DIC-based SHM system is related to solving a number of tasks. One of these is the creation of the so-called Strain Sensor Pattern (SSP) [7] to be appliedto the monitored surface when DIC is used for SHM. Such patterns can be considered as an element of DIC sensors that greatly contributes to the reliability of measurements, determined by their space resolution, sensitivity, accuracy, precision, resilience, reproducibility, and their fast performance.

The purpose of our work is to present a strain sensitive pattern numerically generated by us that is suitable for application to the object’s surface when monitoring at different scales of the images is required. To evaluate the quality of this pattern, we use a criterion, which is an improved version of the criterion for evaluating the effectiveness of such patterns proposed in our previous publication [7].

2. METHODOLOGY

The method of generating patterns is explained in detail in our previous publications [2, 4, 8]. The initial pattern is a "white noise" image, synthesized by a random number generator. The spectrum of this image in the spatial frequency domain is subjected to filtration through a tri-band transmission filter in order to maintain the same image contrast for all frequency domains.

For the purposes of the present work, a binary SSP image obtained from a halftone SSP image having amplitude values of spots at the three frequency bands in a 1:2:4 ratio (Fig. 1) was used. SSP was generated using library OpenCV and Visual Studio 2017 based software. In [8] we have shown that the pattern thus generated ensures high precision, resolution, and resistance to DIC in multi-scale measurements.

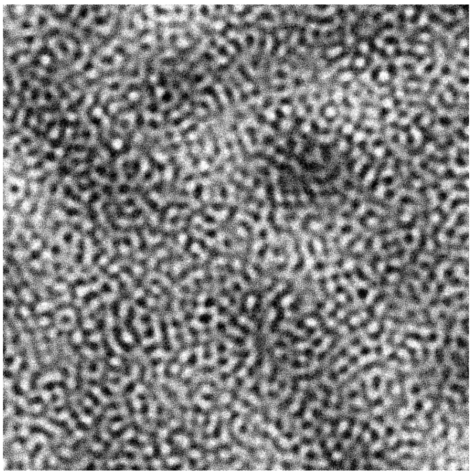


Figure 1. Investigated generated SSP

We propose a combination of the following indicators as a criterion for evaluating the quality of the selected structure:

1. A qualitative factor q, which is determined by the difference between amplitudes of the principal and secondary peak of autocorrelation (correlation) functions in a given subset, in relation to mean square value of the corresponding correlation function [2]:

$$q = \frac{C_{\max} - C_{\sec}}{S(C)} * 100\% . \tag{1}$$

where: $C_{\max}$ is the main peak value, $C_{\sec}$ is secondary peak value, $S(C)$ is the mean square value.

2. The standard deviation of the quality factor values calculated for the different subsets of a given zone of interest (ZOI).

3. Validity factor V. In DIC measurements, it is important to evaluate the image quality of each subset as well as the probability of the measurement being invalid for a variety of reasons (for example - low contrast, lack of pattern's spots in a subset etc.). In this measurement a deformation of the SSP is simulated therefore, it is known in advance, where the correlation maximum for each subset should be sought. In real experiments, not finding the correlation maximum with sufficient accuracy at some subset for any reason would lead to invalidation of calculation results for the respective subset. Due to that for a ZOI, which being considered a certain number N for independent measurements are made across the entire its surface. The validity factor V is defined as the ratio of the number of valid measurements (N_V) to the number of all measurements N:

$$V = \frac{N_V}{N} * 100\% . \tag{2}$$

The ZOI image we analyze has a size of 2048×2048 pixels. A set of subsets sizes has been studied: 16×16 px, 32×32 px, 64×64 px, 128×128 px and 256×256 px. Hundred subsets are randomly selected from this ZOI, but evenly distributed over its area.

In order to determine the application capabilities of the presented SSP it was subjected to computer transformations, simulating plane rotation and uniaxial stretching. The simulation was done with the OpenCV functions.

The first step is a virtual rotation test. Each subset of the computer generated SSP image rotates around the *z*-axis from 0º to 25º through 1º.

The next step is a virtual deformation test. Deformed images are obtained at unidirectional in-plane deformation along the *x*-axis (*x*-direction extension without any deformation along *y*-direction). Deformation of -25 to 25%, in a 1% step is simulated in the entire ZOI area.

The same simulation tests of mechanical transformations were performed at ×10 and ×100 scales.

3. RESULTS AND DISCUSSION

The SSP has been tested with respect to the quality indicators - the quality factors *q*, *D*, and *v* for 5 different subset sizes. A summary of the results are presented in Table. 1.

Table 1. Quality factor *q*, standard deviation *D* и validity factor *V* for different subset sizes.

	16×16 px			32×32 px			64×64 px			128×128 px			256×256 px		
zoom	*q*	D	ν	*q*	D	ν	*q*	D	ν	*q*	D	ν	*q*	D	ν
×1	0.7	1.6	27.7	5.9	5.3	90.9	20.9	10.9	100	81.8	24.5	100	115.5	27.7	100
×10	1.4	2.3	35.4	21.2	5.3	100	38.0	10.3	100	70.4	16.7	100	89.3	16.5	100
×100	0.9	2.4	15.2	16.4	7.8	95.8	61.7	6.0	100	126.1	5.4	100	176.8	2.9	100

When applying DIC-algorithm the aim is to use small-sized subsets to reduce the number of calculations and to minimize the time needed to obtain the result. But as shown in Table 1, when subset's dimension is diminished, the value ofquality factor *q* is reduced. For a good SSP, the standard deviation D of quality factor *q* is small. However, when generating multi-scale SSP, a compromise may be allowed. The *D* value may be large, if *q* is big enough and valid. For validity factor *V*, it can be said that it also decreases when subsets diminish. It can be concluded that in order to obtain sufficiently persistent and reliable results in multiscale SHM, the optimum size of the subsets is 64 × 64 pixels.

In Fig. 2 the function of the quality factor *q* and validity factor *V* from the angle of rotation (Figure 2a) and the deformation (Figure 2b) at scale ×1 (subset size 64×64) are presented. The results from the numerical experiments show that the patterns is maintained until about 5° rotation. At larger degrees of rotation, wrong values of displacements begin to be calculated. From the figure it can be seen also that as the deformation increases, the values of the quality factor *q* and validity factor *V* smoothly decrease to 0. The quality value *q* reduces after 15% deformation.

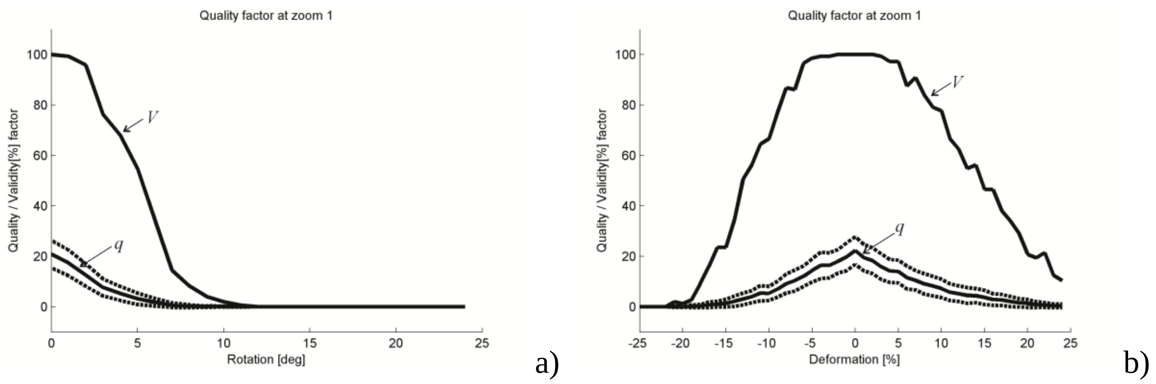
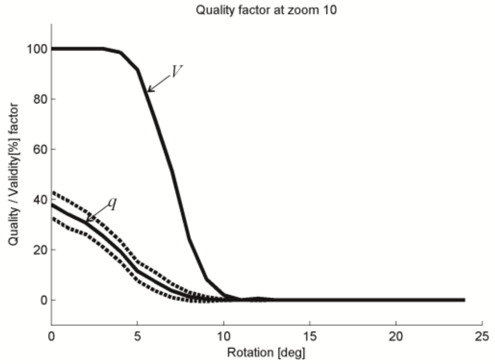
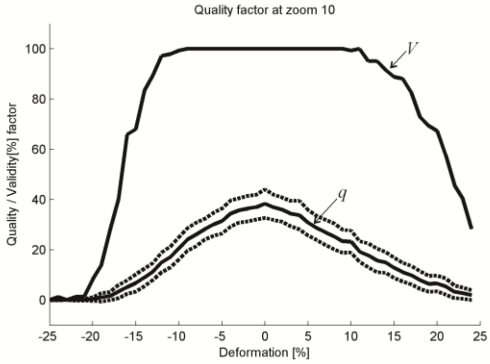


Figure 2. Quality/validity factor vs. angle of rotation (a) and deformation (b)*:* zoom ×1

In Fig. 3 functions of the quality factor *q* and validity factor *V* from the rotation angle (Fig 3a) and deformation (Fig. 3b) at SSP magnification ×10 are presented. Trends in pattern quality are maintained as well as at the scale ×1. Validity factor *V* value begins to fall sharply after 12% deformation and almost reaches zero at 25% deformation.



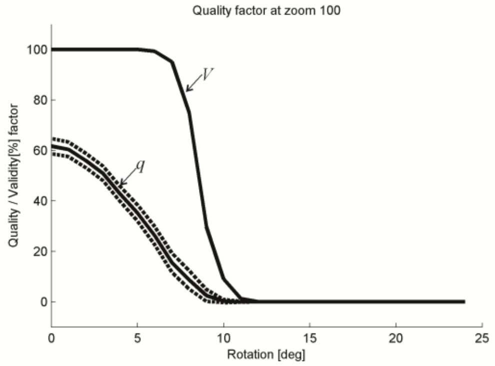
a)



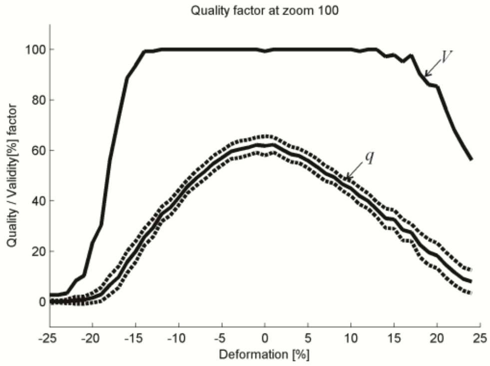
b)

Figure 3. Quality/validity factor vs. angle of rotation (a) and deformation (b)*:* zoom ×10

In Fig. 4, the dependencies of quality *q* and validity *V* factors from the rotation angle (Fig. 4a) and the deformation (Fig. 4b) at SSP magnification ×100 are shown. Validity factor *V* value begins to fall sharply after 15% deformation and almost reaches zero at 25% deformation.



a)



b)

Figure 4. Quality/validity factor vs. angle of rotation (a) and deformation (b)*:* zoom ×100

The presented results show applicability of the SSP we have generated, in monitoring with varying scale of inspected surfaces to about 10º rotation and 20% deformation.

4. CONCLUSIONS

A concept of using DIC technique for Structural Health Monitoring, in which the DIC sensor plays an important role, was presented briefly. The image of a strain sensitive paten was revealed as a key element of such sensor. This image is generated programmatically and is designed to allow monitoring with different scale after its application to the observed surface. SSP quality has been investigated using a criterion we have introduced. In order to determine the possibilities for its applications the image of this pattern has been subjected to computer transformation, simulating in-plane rotation and one-axis tension. The results of the digital experiments prove the applicability of numerically generated pattern to monitoring the inspected surfaces imaged in different scale**.**

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