Making use of Digital Image Correlation to identify the true character of the applied load

Adam Styk*[1], Stanisław Świder[1] and Sergei Semenov[2]

[1]*Faculty of Mechatronics, Warsaw University of Technology, Św. A. Boboli 8, 02-525 Warsaw*
[2]*Department of Wind and Energy Systems, Technical University of Denmark, Frederiksborgvej 399, 4000 Roskilde*

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Abstract—Digital Image Correlation became one of the dominant optical full-field techniques used in experimental mechanics. It does not require sophisticated equipment to evaluate the entire displacement vector field of the specimen under test with great accuracy. In this paper, we would like to draw the reader's attention to the DIC technique as a solution that may identify the genuine character of the load applied to the object under test. Our experience with testing wind turbine blades using DIC proves that possibility.

Almost every technical component or construction requires strict safety standards, including structural strength. Due to that fact, the demand for examining the influence of different loads on various elements is still increasing. However, in many such cases, one relies only on the data about the character of the load generated by the specific excitation system. Consequently, the data's consistency with the applied load's true nature is not verified. Unfortunately, such an approach can sometimes be the reason for obtaining results that are inconsistent with reality, as the two aforementioned load characters may differ from each other. Therefore, this paper presents the use of Stereo Digital Image Correlation to identify the true character of the load applied to the structure under test.

Digital Image Correlation (DIC) is a non-contact optically-based method that can be applied for full-field measurements of the displacement and the deformation of solids. It uses the sequence of digital images of the sample (with a speckle pattern on its surface), which are further correlated to produce full-field coordinates representing the shape, motion, and deformation of the surface of the test piece. The most significant advantages of this method are the independence of the material of the tested sample and the length-scale of interest [1]. Due to that fact, over the past two decades, the number of various applications of these techniques has rapidly increased [2].

Stereo-DIC (also known as 3D-DIC) is one of the types of Digital Image Correlation techniques used to identify 3D deformations or shape measurements of planar and curved objects' surfaces [1]. This method usually requires a stereo pair of cameras (sometimes, a single camera assisted with special light-splitting devices can also be used) [3]. In the case of using that kind of system, it must be calibrated first. This calibration is mainly done with special charts with a specific grid of markers. The next measurement step is acquiring the series of synchronized images, in which each camera records images of the specimen under different loads. The collected images are then stereo-correlated and triangulated. Finally, using these results, the 3D surface of the specimen is computed for every image [4]. After that, it is possible to calculate the full displacement vector of the sample under applied load. The scheme of the Stereo-DIC system is presented in Fig. 1.

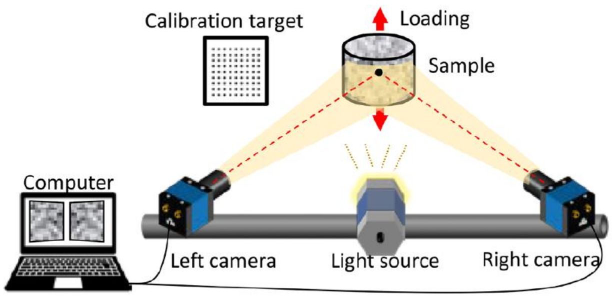

Fig. 1. The scheme of Stereo Digital Image Correlation [2].

In the experiment, we used the 3D DIC system to investigate the behavior of a 31 m Wind Turbine Blade (WTB) subjected to a fatigue test. The main idea was to observe the structure's in-plane ('u'; 'v') and out-of-plane ('w') displacements after an assumed number of out-of-plane motion cycles run with a specific load.

The excitation was realized by the numerically controlled electromechanical system attached to the WTB with pushrods, allowing the movement of the blade structure with different accelerations and, hence, different loads. The control of the load applied to the blade was realized by monitoring the bending moment distribution obtained from the cross-talk calibration from strain values measured by strain gauges located on the outer surface along the blade span. The amplitude of the oscillating load value for each fatigue run was set as a percentage of the maximum bending moment value calculated according to IEC standards [5, 6] for the structure.

* E-mail: adam.styk@pw.edu.pl

The harmonic load of the WTB during fatigue testing was applied with a frequency of 0.964 Hz. However, since the cameras we used for the experiment (FLIR Grasshopper 1394b 50S5) allowed for the maximum capturing speed of 7 FPS, it would lead us to capture only a few frames during the entire motion cycle. Therefore, we have decided to use the aliasing technique and record the consecutive frames every 1.01T, where T is the motion period. This solution allowed us to record 100 samples that recreate the single period of blade motion (under the assumption that the blade motion character is stable over time).

The first step of the measurement (after preparing the experiment and calibrating the DIC systems) was recording images of the wind turbine blade, covered with a speckle pattern, in a stable position. These images further served as reference images for displacement calculation (a sample image from one of the cameras is shown in Fig. 2). In the next step, the blade was excited to the harmonic motion of the frequency mentioned above and with the set load. For different loads and after a selected number of complete motion cycles (e.g., 5000, 10000, 20000), the sets of 100 images, while the blade was still in motion, were recorded. During the entire experiment, over 60 different sets of images were captured.

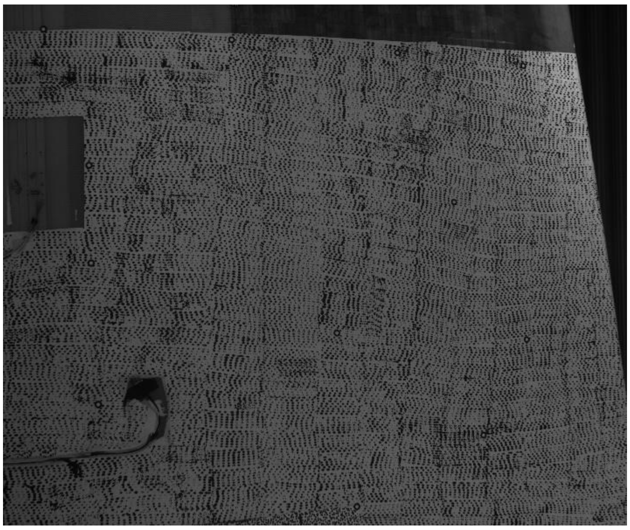

Fig. 2. Sample image of the part of wind turbine blade covered with speckle pattern.

To calculate the out-of-plane displacements ('w') values, the images were processed using specialized software: CCI GUI – the software developed at the Institute of Micromechanics and Photonics, Warsaw University of Technology. It provides tools for image processing using Digital Image Correlation and analysis and visualization of such experimental results. Time changes of the 'w' displacement value over a single period of blade oscillation were measured in three points on the blade's surface (P1, P2, and P3). The spatial location of these points is shown in Fig 3.

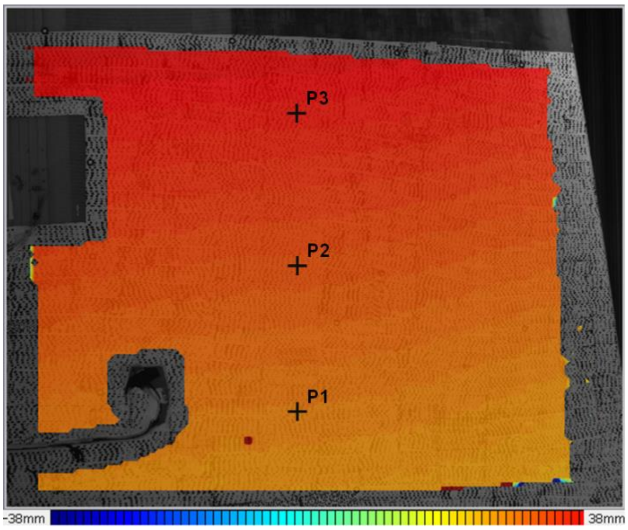

Fig. 3. Sample image with color visualization of the 'w' (out-of-plane) displacement and locations of the investigated points.

Finally, the information on the motion of the structure generated by the electromechanical excitation system and taken from the calibrated strain gauge and those evaluated from the image datasets using DIC algorithms were analyzed and compared.

The allegedly true time changes of the strain values generated during the experiment by the electromechanical excitation system after 5000 cycles for 30% of the load are shown in Fig.4. The entire time series of data consists of thousands of motion cycles, for clarity purposes only two cycles are presented. However, it must be noted that the whole time series character remains the same and, as expected, is sinusoidal.

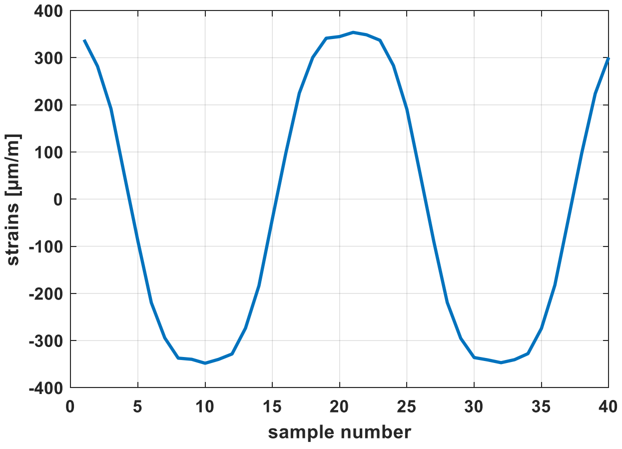

Fig. 4. The plot of strain values obtained from the calibrated strain gauge used for the load control.

The sinusoidal flap-wise load applied to the WTB should lead to the sinusoidal out-of-plane motion of the blade pressure and suction sides. However, after processing the measurement data (as described above), the actual time changes of the out-of-plane displacement in selected blade pressure side points are shown in Fig. 5.

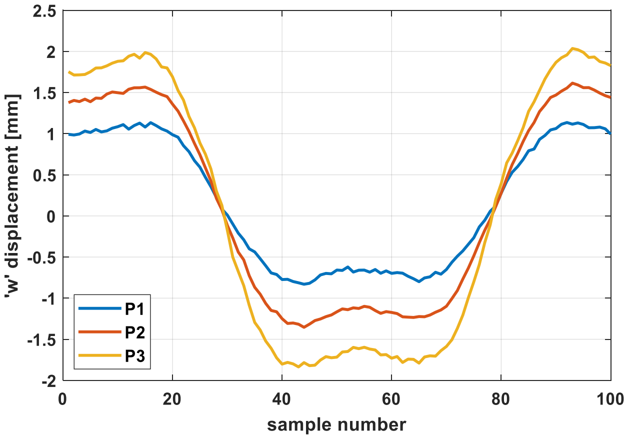

Fig. 5. Initial results of the 'w' displacement measured in points P1, P2, and P3.

Having analyzed these two plots, one can notice that the desired waveform was to be a single-harmonic sinusoid, but the obtained one also consisted of primary and higher harmonics (especially the second one). That leads us to the conclusion that the control strain gauge was calibrated incorrectly. Hence, the load control algorithm oversaturated the force delivered by the electromechanical system, resulting in the measured motion.

After the error in applying the load had been identified, the excitation system was readjusted, and the experiments were carried out. For the new settings of a load system, new sets of 100 images for consecutive loads and after a selected number of complete motion cycles were captured and further processed. The expected results of the WTB motion character were finally achieved (Fig. 6 and Fig. 7).

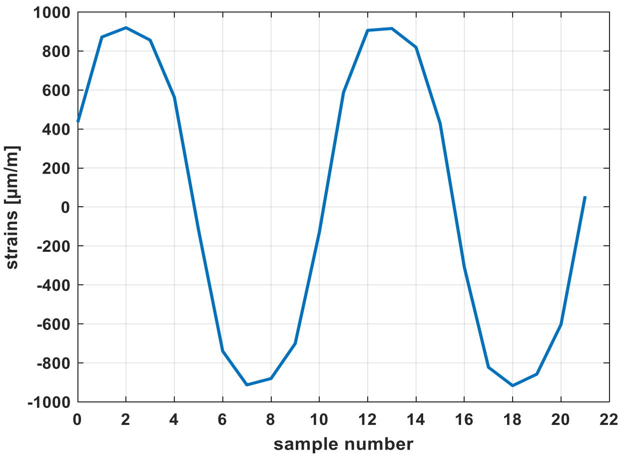

Fig. 6. The plot of strain values obtained from the calibrated strain gauge used for the load control after readjustment.

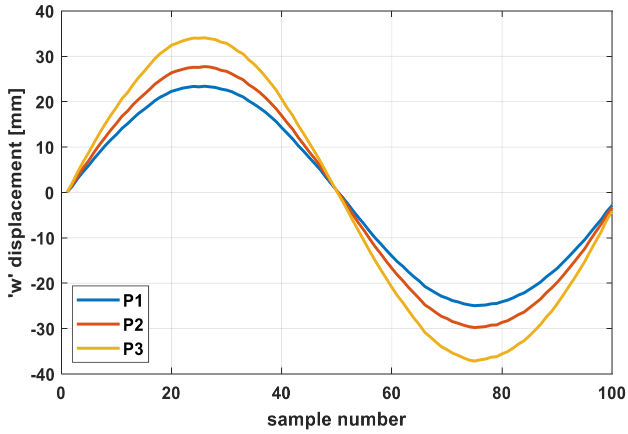

Fig. 7. Results of the 'w' displacement measured in points P1, P2, and P3 after readjusting the electromechanical excitation system.

In summary, the presented results show that the discrepancy between the true character of the load and the allegedly true one (provided by the excitation system) is a real problem, and more attention should be paid to that issue while researching the structural strength of various elements. The described application of Stereo Digital Image Correlation can be used to solve that problem as it provides precise and accurate identification of the character of the load applied to elements under test. On account of that, it would have many practical applications, especially in the industrial environment.

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