Strain Mapping by Digital laser Speckle Correlation, Validation and Comparison

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ABSTRACT

This Paper introduces a new Non-Contact, Optical method for displacement measurements, and strain mapping as well as comparing it to traditional Digital Image correlation (DIC) and laser interferometry measurement method. This Method incorporates diffracted laser speckle images from the surfaces through DIC to track displacement and locate strain values.

In order to evaluate the feasibility of the method, various experiments were done and results were compared to laser interferometry based and traditional DIC. All the experiments were designed and done with affordable equipment, while they resulted in displacement as small as 30 μm detection.

Results presented by this paper are showing that DiLSIC is an economic, accurate, rapid and applicable method for the mentioned purpose. Since it does not require any artifact speckle pattern, it can be used on the non-accessible area, limits and difficulties for creating speckle pattern is not applicable for this technique.

In this research, various magnitude of strains have been examined within the range of [0-10%]. As this technique is a hybrid method of DIC and Laser speckle measurement it could eliminate some of the limits that everyone has. Those removed restrictions include but not limited to being able to measure strain within range of [0-10%] while using fringes on laser speckle does not let the measurement exceed 2%. Also using laser speckle pattern can end all the challenges to achieve the qualified speckle pattern as they can be adjusted to match the requirement easily [1].

Keywords: NDT, Optical Method, Digital Image Correlation, Laser speckle pattern, strain measurement, displacement measurement, strain mapping, full field strain measurement, non-contact measurement, in situ mapping

INTRODUCTION

Exceeding the ultimate strain in loading is one of the most common reasons for a part failure. Therefore, developing an in situ method for strain mapping can lead to prevent the future damages and failure.

Equation (1) is the general equation used for strain measurement under the assumption of small displacement where the Euler and Lagrangian approaches match.

\[ \varepsilon_{kl} = \frac{1}{2} (u_{k,l} + u_{l,k}) \]
As what this equation discloses, tracking displacement is the main step for strain mapping. While Lagrangian reference frame is offering contact methods such as strain gage, Euler derivative of the strain equation can be used in non-contact method such as DIC (add the DIC equation), Speckle Interferometry, Photo- Elasticity, X-ray diffraction and Holographic Interferometry [2].

Digital Image correlation is a measurement technique has been used and known worldwide for displacement and strain mapping [], material property recognitions and defect detection. Not being limited to homogenous and isotropic material, being full-field method can be named as of the advantages of DIC. DIC compares images captured from the object surface before and after applying load. This comparison leads to track deformation and strain measurement on the surface [3-9]. Traditional DIC required fabricated speckle pattern as tools for tracking. Though using this tool is an acceptable and validated technique for DIC, it brought some restrictions. Sometimes we do not have access to the part to apply artifact speckle pattern, or on many cases applying material is not allowed [bio ref]. Also achieving qualified speckle pattern is challenging [10,11]. More of all due to the size of the speckle pattern small deformation is hard to track.

In order to remove some of the restrictions mentioned above, non-contact measurement tools were investigated.

Figure [1] (a) Image correlation is a displacement mapping technique. To create a displacement map, the two images obtained at different strains are divided into smaller subregions. (b) Pairs of subregions are then compared computationally, using correlation or FFT algorithms. The displacement vector joins the center of the subregion and the point of highest correlation. This operation is repeated for all subregion pairs to create a displacement map [13]
As can be seen in figure 1, in traditional DIC, speckle patterns are fabricated to the specimen. The process of applying artifact speckle pattern causes some limits and restrictions [14] which led us to find an alternative way to create speckle pattern.

On the other hand, Laser interferometry has been used widely for strain measurement. These laser-based methods are well known for the accuracy and ability to find the small strain values. Combination of these methods results in developing a hybrid method that uses laser speckle pattern up to track deformation through DIC the following sections are disclosing the validation and comparison steps for this new technique.

Meanwhile, laser-based methods are also used to find defects. This method uses laser speckle interferometry of two laser beams to find the deformation [15] [16]. This method is popular for its accuracy and ability to find the nano-scale deformation. Laser based techniques are widely used due to their high accuracy, feasibility and sensitivity; however, using fringes to measure strain has an important drawback: it will not be accurate in strain values higher than 2% [17].

Individual limitations and similarities of the two methods led to the development of the new hybrid technique which could improve the laser based and DIC techniques a great deal. This hybrid technique takes advantage of laser speckles to track deformation, while the cost-effective setup is being used. [18-21].

EXPERIMENTAL DETAIL

In order to validate the method performance and precision, four executive experiments have been done. Results are compared to laser interferometry and DIC Analysis in the similar conditions [20]. Translation test, tensile test and strain concentration test as well as defect detection test. Figure [2] is showing the set up for translation test. (pull up the exact detail from the thesis).

Figure 2: General Setup for Tensile Test, 40X expanding lens, 632.8nm-30 mW laser, TSI Cannon camera- Lens is EFS 55mm, observation beam, (camera) must be perpendicular to the target surface [23,24]
Translation Evaluation

In translation test, system was expected to track displacement of the part on the translation table with 2.54-micron accuracy. To show the method performance capability in tracking displacement for different surface roughness, variable materials (and finishes) have been used such as Al sheet, uniformly painted Al sheet and rubber. After validating the performance of DiLSIC in translation detection, we moved forward with rubber material (due to high flexibility) with in the rest of steps (find from the thesis). Displacement was applied in the domain of [30micron and 25,400 micron) to evaluate the system limits. The sample geometry was a regular 126mm × 25.4mm rectangle. Results of the translation test can be found in figure 2.

![Sample Images](image)

(a) (b) (c)

Figure 3: Sample used in translation test (a) Aluminum sheet with texture (b) Uniform painted aluminum sheet (c) Rubber sample on the white background

The camera used in all parts was T5I Cannon camera- Lens is EFS 55mm. To find the best setup for the camera, images with different apparatus size and exposure time were capture. Then, the resulting histograms showed the best setting for the camera setup as 8 for aperture size and 1.3 seconds for time of exposure.

Below figures show the results for translation evaluation through DiLSIC (both numerical and visual). Matching results with the actual displacement are a proof of DiLSIC capability in tracking displacement. While theoretical calculations proof that incorporating images through DIC cannot exceed 0.02-pixel size, only 0.4% error in the results can be considered as a great accuracy and capability.

![Displacement Contours](image)

Figure 4: Resulting displacement contours for rubber sample in translation test. Pixel size was 0.031mm. The uniform color of contours shows the rigid body motion.
One of the main limits of using traditional laser interferometry is not being able to recognize translation movement. This fact restricts inspected specimen to be fixed on a support. While in many cases such as in vitro bone analysis, it cannot be guaranteed [22].

**Tensile Test**

Tensile test has been done with rubber to evaluate the method performance in strain measurement. Results were compared to DIC for validation. Displacement load was applied along the X axis to the one end of the sample while the other end was fixed at the tensile test device support. The device accuracy is 25.5 micron as well. Strains of 1% to 10% were applied to one end of the sample. The same tests were done with the traditional DIC. Figure [6] is showing the DIC and DiLSIC samples. As can be seen in this figure, paint has been applied to the DIC sample as the fabricated Speckle Pattern

**Figure 6: Sample used in tensile test with DIC (right) and sample used for DiLSIC (left)**

Figures below show the visual and numerical comparison between DiLSIC and DIC in strain measurement. As can be found, DiLSIC could achieve more comparative results in strain less than 2% in compare to traditional DIC. They
both achieve good results in strain more than 2% while laser interferometry is not capable of measuring strain more than 2% [16].

![Figure 7: Comparison between DIC (right) and DiLSIC (left) resulting contours after tension. Actual strain in both cases was 6%](image)

Figure 7: Comparison between DIC (right) and DiLSIC (left) resulting contours after tension. Actual strain in both cases was 6%

![Figure 8: Strain comparison between DiLSIC and DIC chart](chart)

Figure 8: Strain comparison between DiLSIC and DIC chart

It is also worth mentioning that in tensile test for strain measurement, DiLSIC resulted in values with mean error of 1% while the same value for traditional DIC was 1.8%. [20]
**Strain Concentration**

In this step, a 10mm diameter hole was created on the samples to investigate DiLSIC performance in strain mapping. It was expected to be able to detect the strain concentration as well as locating the critical area (points). Again, results were compared to DIC results. Random points aligned an imaginary vertical line passing from the hole center were picked for the strain value comparison with the points at the same coordinates at the DIC sample.

![Figure 9: Deformed sample in tensile test in DiLSIC (left) and DIC (right) method.](image)

Figure [10] and [11] are presenting the results and comparison of strain mapping and strain concentration detection in both DIC and DiLSIC methode. High agreement in visual contours and numerical values is a further proof and validation for DiLSIC capability in strain mapping.

![Figure 10: Strain concentration contour- DIC (left) and DiLSIC (right) results comparison](image)
Figure 11: Comparison between DIC and DiLSIC in strain concentration detection. The high agreement between results is the other evidence of DiLSIC performance precision.

CONCLUSION
A new hybrid method was evaluated and compared to a few other strain mapping techniques. This method could combine the advantages of both laser based and DIC methods to eliminate some of the problems from each individual method. The performance of this technique in finding defects, strain measurement, and strain concentration was evaluated in all experiments. The comparison between DiLSIC and DIC and traditional laser interferometry measurement methods is presented in the table below.

| criteria                        | Traditional Laser Interferometry | DIC         | DiLSIC     |
|---------------------------------|---------------------------------|-------------|------------|
| Capable of translation recognition | No                              | Yes         | Yes        |
| Specimen preparation            | Not Required                    | Required    | Not Required |
| Capability of Strain Measurement Range | Only less than 2% | [0%-10%] Has been validated | Only more than 2% |
| Strain Measurement Accuracy     | Maximum for Values less than 2% | 1.8% error  | 1% error   |

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