

# Strain Measurements by Full-Field Optical Techniques

Hamid R Eslami, Rasoul Rashidifar

Department of Mechanical Engineering, University of Texas at San Antonio, One UTSA Circle San Antonio, San Antonio, TX 78249, USA

## Abstract

A weak position and possibly leads to make a defected material and production. Localized strain concentration is becoming very important in the area of quality assurance. Recently, there are many research that researcher proposed using Computer-Aided-Engineering (CAE) tools to reduce the number of prototype builds and to speed up the development cycle. In this paper, there are some literature about researches that conducted in this field. The capabilities as well as the limitations for industrial applications are investigated. An application of this method is demonstrated on a stamping die to validate a FEM results. Full-field methods of strain measurements are very broad and many number of these techniques are using and can be widely categorized to two groups as Geometrical methods and Interferometric methods.

## Introduction

In the last decade, many new and modern tools and methods have been developed to measure and find some experimental parameter such as stress, strain, force and energy. One of the great method that researcher incline to use that is FEM, they use some FEM software to simulate or coding a program to find and predict these kind of parameters [1]. Also some papers are some new and modern materials that are using in this field[2]. Other methods that can be mentioned are using electromagnetic method to find displacement and even force[3], in this case some researchers developed some optimization algorithm and machine learning framework to optimize and predict parameters like displacement, strain, stress, energy and so on [4], [5]. Full-field methods of strain measurements are very broad and many number of these techniques are using by laboratories these days. These methods can be widely categorized to two groups as Geometrical methods and Interferometric methods. Geometrical methods are such as grid methods, moire or digital image correlation methods, and interferometric methods, include holography, moiré interferometry, ESPI or photo-elasticity. Improvement in new optical equipment enhanced by computer and information technology, have made these techniques very well developed tools for material investigations and study the material structure. Displacement measurements and strain measurements are features which can characterize material properties. Recently, these fields have led to new hybrid to identify materials properties. Selecting the most relevant technique is even a valid question, now. Moreover, many universities, labs and researcher are exploring how to control and quantify the performance of these methods, these are questions which have not been solved yet. Material researchers are working to dominate basics of data analysis, optimization and optical techniques to select the most reliable full-field method. Since many parameters are playing role here, it is hard to select the most efficient process of measurement method and it is a problem which has to be seen as whole to choose a comprehensive method. In the following, the most popular methods of measurement will be explained in two broad category of Displacement measurement and Strain Measurement.

## 1. Grid method

In this method images of specimens which carry a regular marking like a grind that has been deposited in plane deformation, are processed to measure in-plane displacement and strain components. The idea has been around from many decades ago, since it enables the experimenters to easily distinguish a pattern or points on a deformed surface and make it easy to track them during the deflection [6].

Among literature of 60's there are many papers explaining how to build a grid and distribute points to consider their intersections of the lines or the points inside the cells and establish a mesh of grids. The basic stand upon measuring the coordinates of the selected points and compare the displacement with the reference by subtracting the new deformed coordinate by the original un-deformed one. Nowadays, computer, AI and image processing enhance this method tremendously, in which all the process of meshing, selecting the points, and then comparing the deformed mesh by the reference one are calculating by computers, precisely [7]. This technique used to be applied for large deformations and displacements like sheet metal forming and concrete pillars. However, it is rare to see any application of this method on those material testing, and it seems that it is going not to be used anymore, due to excessive application of image processing which avoids experimenters to use mesh and calculate coordination. The emergence of Digital Image Correlation (DIC) has filled the position of this method in laboratories [8]. DIC method will be explained in the next section.

There are different techniques to deposit grids on a specimen. Among those old techniques there are some which are still valid, and specially printing technology have enabled us to do that better, but generally the quality of the delivered grids are not available anymore, because of the reached pitches. Therefore, it is recommended to improve grid techniques from nest to a large scale to mark a specimen with a grid pattern. The finer grid leads to better resolution and any formation can be caught. Using scanning electron microscope (SEM) the finest possible mesh for an in-plane deformation can be considered. With SEM the atomic lattice of the substrate of the specimen can be considered as a grid, and then every deflection will be captured using image processing algorithms. In this way the grid pitch is in the order of angstroms.

There some other techniques which can be used to achieve higher scale of grids, such as metal sputtering in tribology, or etching of the specimen in Electro Chemical Machining which can create microgrids on the surface of the specimen.

To calculate the deformation on the surface of the object, a grid is deposited by one of the methods were explained above, by pitch of  $P$ . This grid can be considered as a simple parallel straight lines on the surface. These lines plays a role as a spatial carrier, in another words displacement field  $u(r)$  is calculated as following:

$$\phi(r) = 2\pi \frac{u_x(r)}{P}$$

$U_x(r)$  is the displacement component of  $r$  which is perpendicular to the lines. Simply with a pitch of 0.5 mm and a phase resolution of  $2\pi/100$ , a resolution of 5 micrometers is achieved.

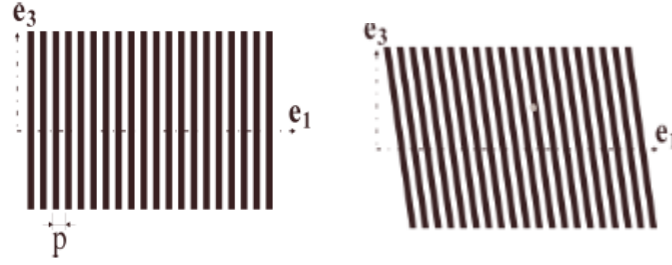


Figure 1: a) Initial state of the grid, b) final state after deformation

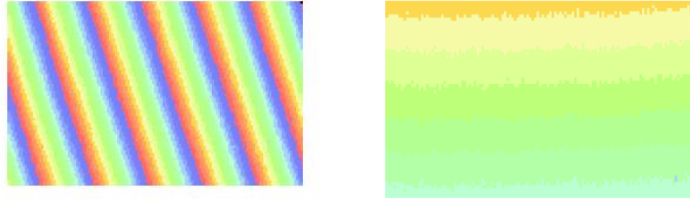


Figure 2: a) Final fringe pattern  $\phi(r)$  extracted, b) final displacement pattern  $u(r)$

Figures 1, and 2 shows how displacement is calculated and what is the difference between of the patterns in the beginning and final grid pattern in the region which been exposed to a constant moment of a beam in 4 point bending [9].

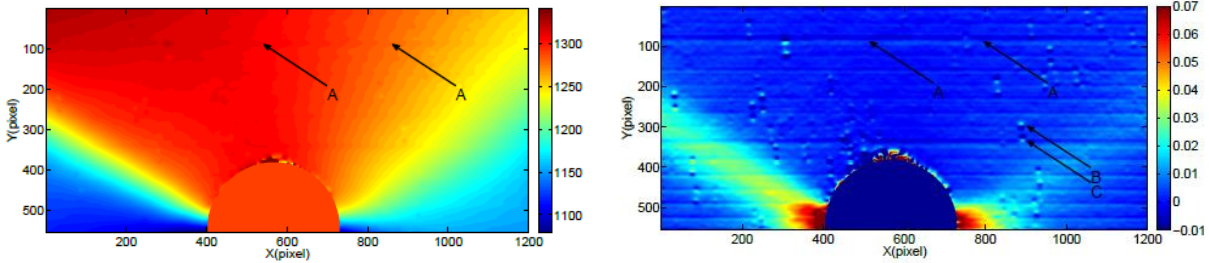


Figure 3: Illustrative example of the impact of grid defects on the displacement and strain maps, and defect removal by displacement compensation. a) vertical displacement  $U_y$  (in micrometer). b)  $\frac{\partial u_y}{\partial y}$  distribution.

## 2. Image correlation

One of the most popular of geometrical techniques is image correlation. In this method, a same image is taken from the desired zone of the specimen in two conditions. One when specimen is in its original shape, and the other when specimen is under load and has been deformed. Surface of the sample is marked by paint. This image has to be divided to some smaller images which are typically 10 to 20 pixel size. A cross correlation is taken place later between each sub images and the final image. The position of the corresponding signals shows the transformation of the area respect to the sub-image between to states. Precision of the displacement in this method is in an order of a fraction of pixel, which is usually 1/50 pixel, but the spatial resolution is poorer as the size of the sub-image.

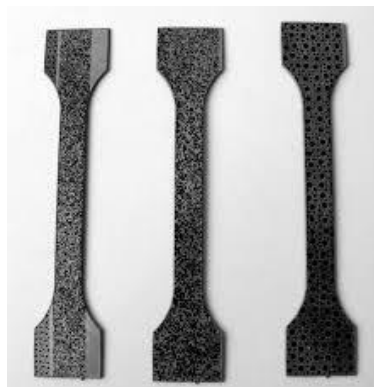
### 2.1. Digital Image Correlation

Digital image correlation, as mentioned above, include both geometric and interferometric techniques. The optical metrologies compares the difference of the scattered phase light wave from the surface of the specimen before and after loading and in this way measures the deformation. On the other hand, geometrical techniques compares the gray scale variations of the surface of specimen and calculates the deformation while object is opposed by the load. The DIC method was invented in the University of South Carolina in 1982, but it grows so fast after 1990s due to the digital revolution which influenced photography industry and digital cameras which became available in the market. Computers enhanced by huge memories and

high resolution digital cameras were capable of achieve full-field measurement. One of the advantages of the DIC is that deformation of any materials and structures can be measured by this method as long as it is subjected to incremental loading process and deformed and un-deformed digital images can be compared together. This is technically a photogrammetry method which uses computer vision to find out the similar points. In DIC series of images of a sample compares with each other at diferent stages of the loading. DIC basically follows movement of pixels in the desired area and based on that calculates the displacement and strain by tracking those points in different photos. In a 2D-DIC only one single camera is needed to record many images while specimen is loaded and deformed. Then images of the planar sample which is connected to the specimen is transformed to a computer to process them. This method compute in-plane displacements and strains at the surface of the specimen. However, the 3D-DIC technique needs two fixed cameras taking images simultaneously and a 3D structure is created based on the binocular stereovision. The 3D displacement can be measured by tracking the deformation of versatile planes in those images [10].

2D and 3D DIC are used in civil, and mechanical engineering with using available commercial softwares. Open source softwares are being paid attention these days, since they are more user friendly and are cheaper, also users can adjust them based on their needs. Some of those open source softwares have been developed by MATLAB and are available freely to the scientist and academic users. These research DIC free softwares, include NCORR and also PY2DIC which has been developed in the University of Rome.

2D – DIC is more popular and practical in displacement measurement. To do a 2D test of DIC a pre-test specimen usually prepared with a speckle pattern which is deposited by spraying to the surface of the sample (**Figure 4**). Spry on to the surface of the specimen depends on its natural pattern on the surface. Sometimes the pattern is enough to be able to make a mesh and be visible in the camera, therefore there is no need for marking. The number of photos taking by camera is also chosen based on the speed of the experiment, however it is usually taken 50 to 100 images per experiment. The first image definitely is considered as the reference photo, which means the sample oppose to no strain or displacement. In the following, each image is divided to small sub-images and the pattern in each sub-picture of corresponding image is compared to the reference image. Then the displacement for each node in all subsets are calculated and strains are achieved based on that. By doing test on one sample, all displacements, axial and transverse strains, and corresponding shear strains and minimum and maximum strains are computed [11].



**Figure 4: Typical Speckle Pattern applied to a test sample**

Displacements and strains are mapped on an image like Finite Element Analysis (FEA) reports (**Figure 5**). This type of reports can be very useful comparing the result of FEA with the experimental results. In the past, to verify FEA modeling results, researchers had to compare the results of a FEA analysis by the simple data were provided in the experimental tests by extensometers and strain gauges. However, using DIC

scientist are capable of comparing the changes of every single point of the materials in the specimen by their prediction simulation in FEA. But it does not mean that those old school strain gauges are not applicable any more. Even using DIC, those strain gauges are used to verify the results on DIC softwares, and DIC softwares these days are capable of acquire those data as well.

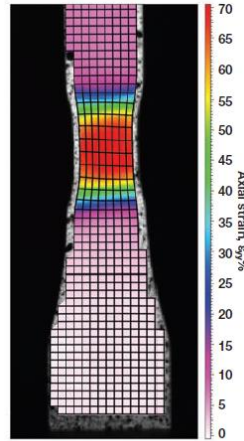


Figure 5: Sample DIC Strain Map

## 2.2. DIC as a teaching tool and more

Some reasons that make this visual method (DIC) a powerful teaching tool for materials science and engineering courses at the universities are the DIC method is an appropriate tool to observe failure in action and also it has the capacity to analyze and reanalyze data. For instance, by using this method, strain is determined as a “V” shape across the sample and finally it causes the sample to fail angled across in a metal testing. It is shown in **Figure 6**. By using DIC, measurement of strain from real specimen is feasible, however observing behavior of it without a simulation is very difficult and challenging. In this case, changing strain either close or away from the failure point is shown by using strain gauges and virtual extensometers that are set up in different location along the sample. These results make DIC an understandable visual representation to show that how failure occur and it enhances its capability for being a valuable teaching tool. Moreover, DIC for test specimens and samples with non-uniform strain distribution throughout the material can be used. It needs to be mentioned that there is no enough information about the test piece deformation and strain provided by strain gauges and extensometers. For instance, in a sample including a through-hole it is clear that stress concentration is around the hole and there would be a non-uniform strain pattern. Strain gauges show the strain is greater around hole while by using DIC it is shown that where the peak strain is and how strain forms at the point of material failure.

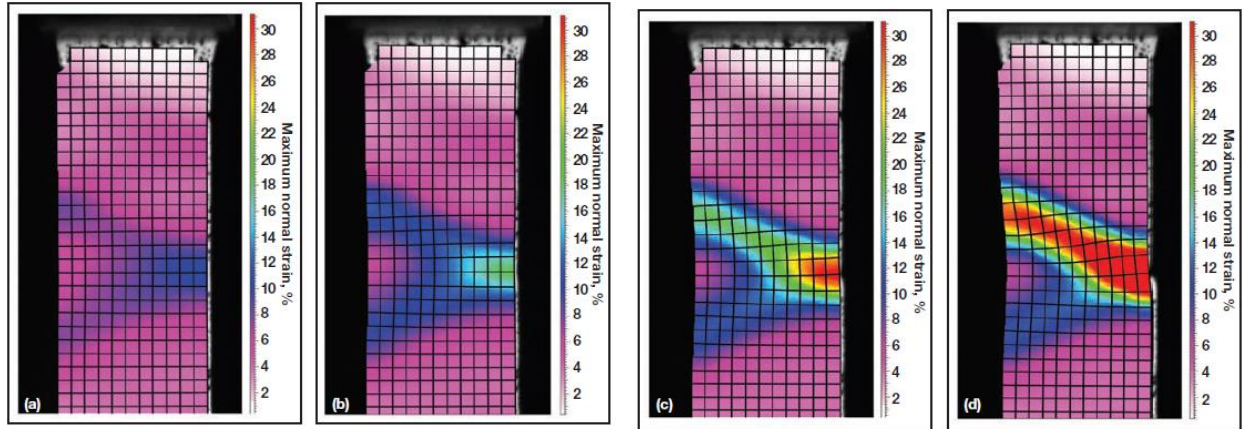


Figure 6: DIC strain maps of a metal proceeding to failure

The results for this case is shown in **Figure 7**. Concentration is around hole and there are maximum of axial strain to the left and right and minimum above and below of the hole. DIC need to meet current test standards so, it does not seem that it can be replaced traditional extensometers and strain gauges in near future. However it is a suitable tool to understand the complexities of modern materials in researches that are conducting in universities.

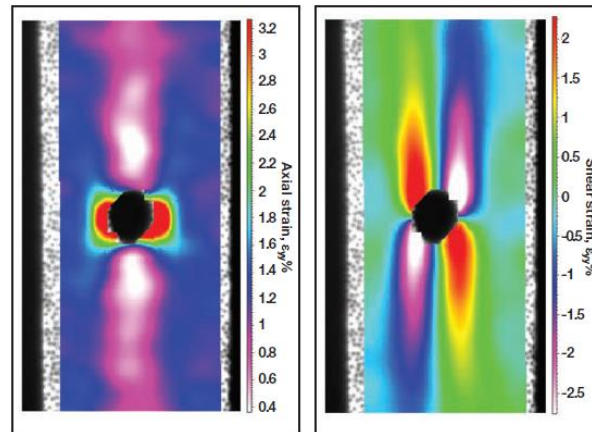


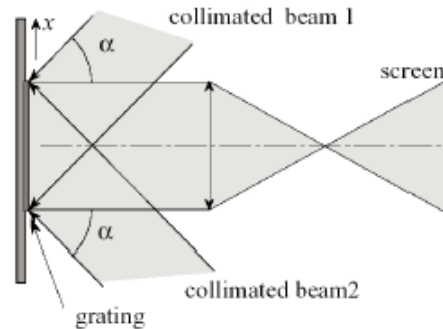
Figure 7: Axial (left) and shear (right) DIC strain maps for a through-hole specimen

### 3. Interferometric moiré

This is a technique that uses the wave optics phenomenon of diffraction. Onto the specimen, A grating (i.e. a pitch with micrometric pitch  $p$ ; typically,  $p = 1200$  lines/mm, maximum size: 50 mm) is moulded and by two symmetric oblique collimated beams is illuminated. The light interferes is located on the screen where the image of the grating area (**Error! Reference source not found.**). The interferometric fringe phase variation due to loading is: [12]

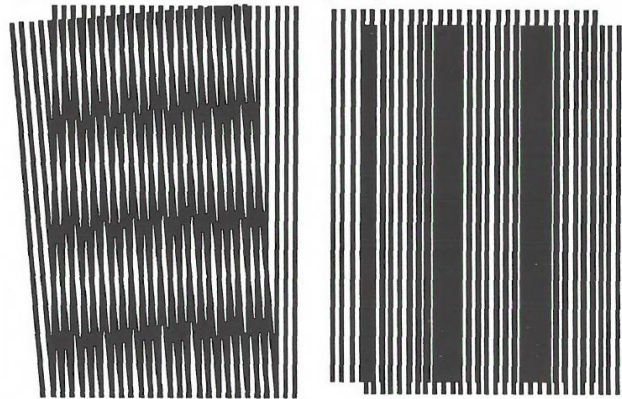
$$\phi(r) = \frac{4\pi}{p} u_x(r)$$

With a pitch of  $1 \mu\text{m}$  and a phase resolution of  $2\pi/100$ , a resolution of 10 nanometers can be achieved. The spatial resolution is equal to few micrometers, by using a microscope, the region of interest may be observed.



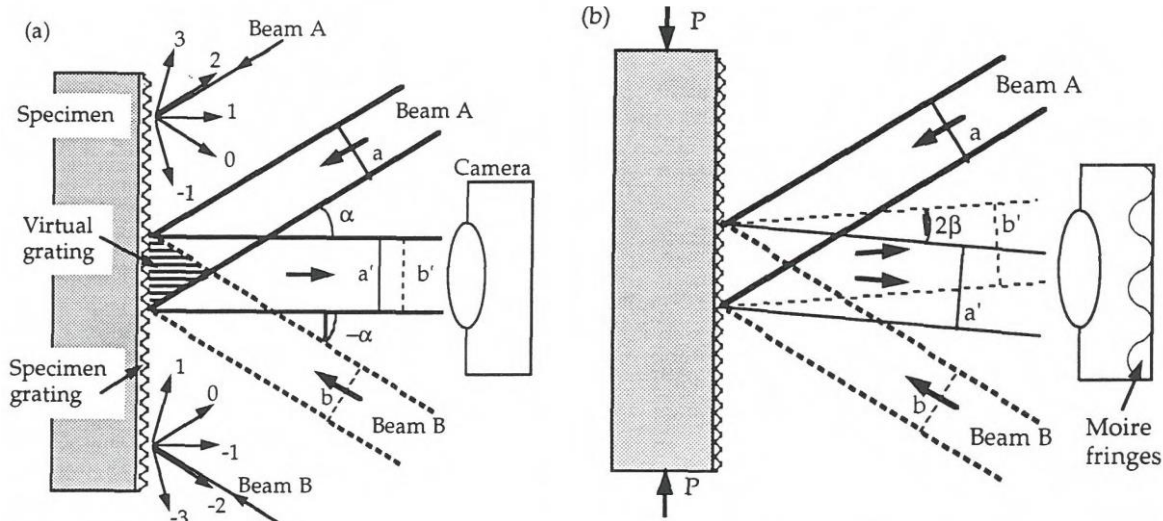
**Figure 8: Interferometric Moiré Setup**

In **Figure 9(a)** a simple example for Moiré effect is shown. In this example, two identical line gratings are superposed. If one grating is fixed and the other is rotated a little bit rather than fixed one, a system of fringes perpendicular to the grating lines would arise. The spacing between the moiré fringes is reduced by an increased angle. Another case is shown in **Figure 9(b)**. In this case, the two gratings are parallel with a little different pitch. If a small rotation take place on one grating there would be a larger rotation of finger pattern.



**Figure 9: a) Moiré between two gratings with different orientation. b) Moiré between two gratings with different pitch**  
Moiré can be used to measure deformation. In this case, two superposed line gratings are considered that one of them is set up on deformed grating and the other would be a static reference grating. Displacement contours of the specimen grating relative to the reference grating is shown by the moiré fringes that arise in the direction perpendicular to the gratings. The grating frequency determine sensitivity to displacements with a grating pitch  $p$  each moiré fringe represents a displacement of  $p$ . Increasing the grating frequency is one way to increase the sensitivity for displacement. Moiré using amplitude gratings as in **Figure 9** is called geometrical Moiré. The spatial frequency of 40 lines/mm or lower usually is used in geometrical moiré the gratings and diffraction phenomena gets disturbing at higher frequencies. The diffraction characteristics of grating is applied in Moiré methods with higher grating frequencies than 40 lines/mm. Moiré interferometry is a moiré method with high sensitivity for in-plane displacement. A grating frequency of 1200 lines/mm is common but gratings with up to 2400 lines/mm has been used. Since the sensitivity for displacement is twice the grating frequency, a 1200 lines/mm grating gives a sensitivity of 2400 lines/mm with each Moiré fringe corresponding to a displacement of 0.417  $\mu\text{m}$ . A set-up for high magnification moiré interferometry is described and demonstrated. **Figure 10**, the principle of Moiré interferometry is shown, where two coherent and collimated laser beams illustrate the specimen grating. The angle  $\alpha$  is determined so to the specimen grating, +1 diffraction order of beam A and -1 diffraction order from beam B is normal. In this case unlike moiré methods only one real grating is used in moiré interferometry and instead interference between A and B forms a virtual reference grating from alternating constructive respective destructive

interference in front of the specimen. In other moiré methods this virtual grating behaves such as a static reference grating. For displacement it gives a doubled sensitivity and has the double frequency of the specimen grating. These explanations mentioned above can be considered to other moiré methods since the moiré fringes would be identical if the reference grating was a real grating instead of a virtual grating. The things that is considered in **Figure 10** about the un-deformed specimen gating can explain more about Moiré interferometry. In diffracted beam which are normal to the sample and specimen the plane wave fronts  $a$  and  $b$  remains plane. Between the beams in the camera plane, there are a constant phase difference giving a constant interference pattern while the wave fronts  $a'$  and  $b'$  are exact parallel. This constant intensity is a so called null field with a fringe spacing going to infinity [13].



**Figure 10: Principle of Moiré interferometry. a) Undeformed Specimen, giving a null field. b) Specimen subjected to homogeneous pressure  $P$  resulting in a regular Moiré fringe pattern**

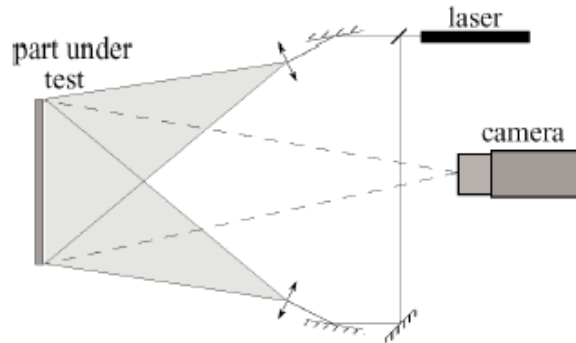
Also, with assumption that the deformation is homogeneous and small, if the specimen is deformed, the frequency of the grating would be altered. **Figure 10(b)** shows that the diffraction direction will be changed by the change in grating frequency by an angle  $2\beta$ . The wave fronts  $a'$  and  $b'$  are no longer parallel giving a varying phase difference. The two beams are collected by camera lens and an interference pattern at the image will be created by this phase difference. When a non-homogeneous deformation of the specimen occur, it gives varying grating frequency and the wave fronts  $a'$  and  $b'$  will be warped but continuous. From the interference between the two wave fronts in the image plane the moiré fringes would be appeared and it would show the deformation in each point on the specimen.

#### 4. Speckle (ESPI)

The speckle setup (**Figure 11**) is very similar to the moiré interferometric one, except that no grating is required here. It causes this method to be able to investigate a larger area with diverging beams that is a reason that this technique is more handy and popular. The counterpart is that extensive spatial noise is present.

The spatial filtering which is necessary to remove part of this noise severely decreases the spatial resolution. The relationship between the fringe phase variation and the displacement is the same as above:

$$\phi(r) = \frac{4\pi}{\lambda} \sin \alpha \cdot u_x(r)$$



**Figure 11: In-plane speckle setup**

It needs to be mentioned that the angle of incidence varies across the field, due to the non-parallel illumination. The resolution on displacement is comparable to the one of grating interferometry. The spatial resolution depends on the numerical aperture of the objective lens and it is at least the speckle size. When a CCD camera is the sensor, it is considered that the aperture should be chosen so that the speckle size is of the order of the pixel size. But the most significant point in this case is that speckle noise should be removed in an extensive smoothing, so the spatial resolution may increase to 30 to 60 pixels. Users or manufacturers should consider this crucial point.

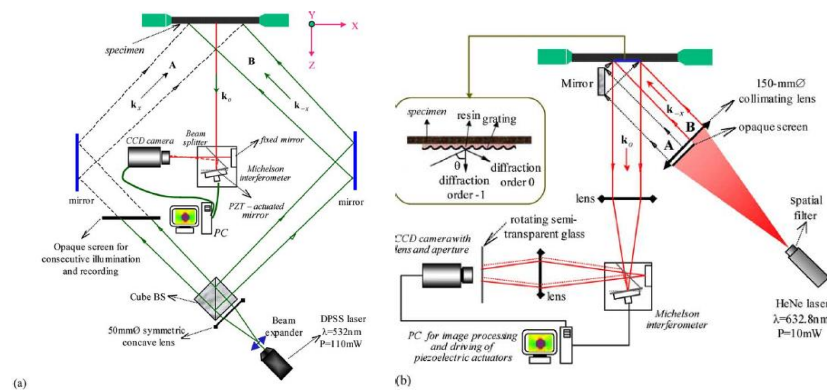
For characterizing whole field deformation and strain together with digital image correlation (DIC), DSPI is used [14]. For measuring small deformation in the order of submicron to a few microns DSPI is a preferred tool, however DIC is a powerful technique because this method has higher sensitivity than DIC. There are two limitations in DSPI systems for a sample that has a complex surface with a significant contour change and three DSPI layouts. The simply differentiating the measured deformation data cannot determine a complex surface strain. Namely, for appropriate determination of strain for a curved surface, both deformation and contour data are required. Second, the present three DSPI layouts for 3D measurements are based on an assumption that measurement sensitivity is constant. However, there would be a considerable variation if a sample size is not significantly smaller than a working distance (distance between the sample and the sensor).

## 5. Grating shearography

In **Figure 12**, The optical setups for speckle shearography (a) and grating shearography (b) are illustrated. The descriptions on both figures show that both methods have the same elements. In **Figure 12(a)**, a beam expander and a 50-mmB lens to regulate the expansion ratio of the beam illuminating an object are employed and the beam splitter and two mirrors are used to realize two slightly expanded beams, A and B. It is chosen a 110-mW Diode-Pumped Solid-State laser with a wavelength of 532 nm on account of the high laser power requirement of speckle metrology. In **Figure 12(b)**, a spatial filter, a 150-mmB collimating lens and a mirror is used in this system. Contrary to speckle shearography, a 10-mW HeNe laser with the wavelength of 632.8 nm was adopted. One of the disadvantages of speckle shearography is that it needs to have the high laser power requirement, practically in realizing the illumination system in its optical setup. Generally, both systems are equipped with a modified Michelson interferometer as a shearing and phase-shifting device. For preparing a specimen there is a significant difference because of the mediums for a fringe pattern are different.

First, speckle shearography is based on the speckle pattern that appears as a fluctuating intensity distribution. As in **Figure 12a** has been shown the sheared and speckled image is formed in the image plane, where the two waves separated by tilting the PZT-actuated mirror interfere each other.

Second, grating shearography is based on the use of a diffraction grating fixed on the specimen that in **Figure 12(b)** is shown. Similarly with speckle shearography, the beam diffracted from the grating is separated by the shearing element. In a fringe pattern the interference between two diffracted beams directly gives rise and the same temporal phase-shifting methods as speckle shearography can convert it into a phase fringe pattern. The map is changed by the phase and the subtraction of the reference phase fringe pattern map obtain this phase from the deformed one and the grating acts as the sensor for grating shearography. Using discrete Fourier transform algorithm is a common method to determine the phase, and the software Frangyne developed from INM (French National Institute of Metrology) is used for both shearography systems to control PZT elements for driving the movable mirror and to process image data. In the speckle shearography method, the camera observe the virtual images directly whereas in grating shearography the real images focused by two lenses before and after the Michelson interferometer are observed on a rotating semitransparent glass plate, which performs the optical filtering by averaging temporally speckle noise [15].



**Figure 12: Optical Setup. a) Speckle shearography and b) grating Shearography**

## References

- [1] R. Rashidifar, M. Khataei, M. Poursina, and N. Ebrahimi, "Comparison and Evaluation of Criteria Ductile Damage FLD & MSFLD to Predict Crack Growth in Forming Processes," 2014.
- [2] R. Rashidifar, J. Jafari, H. Shahriary, and V. Jafari, "Analysis of FGPM cylinder subjected to two dimensional electro thermo mechanical fields," *Modares Mech. Eng.*, vol. 14, no. 4, pp. 83–90, Jul. 2014.
- [3] Jafari, Amir, and Nafiseh Ebrahimi. "Electromagnetic soft actuators." U.S. Patent Application No. 16/457,452.
- [4] N. Ebrahimi, T. Guda, M. Alamaniotis, D. Miserlis, and A. Jafari, "Design Optimization of a Novel Networked Electromagnetic Soft Actuators System Based on Branch and Bound Algorithm," *IEEE Access*, vol. 8, pp. 119324–119335, 2020, doi: 10.1109/ACCESS.2020.3005877.
- [5] R. Rashidifar, "Estimation of Energy Performance of Buildings Using Machine Learning Tools," *engrXiv*, preprint, Jun. 2020. doi: 10.31224/osf.io/4esdw.
- [6] M. Grédiac, F. Sur, and B. Blaysat, "The Grid Method for In-plane Displacement and Strain Measurement: A Review and Analysis," *Strain*, vol. 52, no. 3, Art. no. 3, 2016, doi: 10.1111/str.12182.

- [7] R. W. Fail and C. E. Taylor, "An application of pattern mapping to plane motion," *Exp. Mech.*, vol. 30, no. 4, Art. no. 4, Dec. 1990, doi: 10.1007/BF02321512.
- [8] T. C. Chu, W. F. Ranson, and M. A. Sutton, "Applications of digital-image-correlation techniques to experimental mechanics," *Exp. Mech.*, vol. 25, no. 3, Art. no. 3, Sep. 1985, doi: 10.1007/BF02325092.
- [9] S. Avril, A. Vautrin, H. Patrice, and Y. Sirel, "Local and global analysis of cracked reinforced concrete beams repaired with CFRP laminates.," Jan. 2002.
- [10] P. Caporossi, P. Mazzanti, and F. Bozzano, "Digital Image Correlation (DIC) Analysis of the 3 December 2013 Montescaglioso Landslide (Basilicata, Southern Italy): Results from a Multi-Dataset Investigation," *ISPRS Int. J. Geo-Inf.*, vol. 7, no. 9, Art. no. 9, Sep. 2018, doi: 10.3390/ijgi7090372.
- [11] "Technical Spotlight: Using Digital Image Correlation to Measure Full Field Strain," p. 2.
- [12] D. Post, B. Han, and P. G. Ifju, "Moiré Methods for Engineering and Science — Moiré Interferometry and Shadow Moiré," in *Photomechanics*, P. K. Rastogi, Ed. Berlin, Heidelberg: Springer, 2000, pp. 151–196.
- [13] L. G. Melin, "Moiré techniques for measurement of the deformation field at crack tips in fiber composite materials," 1995. <https://www.semanticscholar.org/paper/Moir%C3%A9-techniques-for-measurement-of-the-deformation-Melin/d86b68838bf86a5e20ee198997f7b3c41d63cdc9> (accessed May 12, 2020).
- [14] Y. Wang, D. Thomas, P. Zhang, H. Yokota, and L. Yang, "Whole Field Strain Measurement on Complex Surfaces by Digital Speckle Pattern Interferometry," *Mater. Eval.*, vol. 66, no. 5, Art. no. 5, May 2008.
- [15] J.-R. Lee, J. Molimard, A. Vautrin, and Y. Sirel, "Application of grating shearography and speckle shearography to mechanical analysis of composite material," *Compos. Part Appl. Sci. Manuf.*, vol. 35, no. 7, Art. no. 7, Jul. 2004, doi: 10.1016/j.compositesa.2004.01.023.