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IMPACT OF SPECKLE DEFORMABILITY ON DIGITAL IMAGE CORRELATION

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Abstract:

The Impact of Speckle Deformability on Digital Image Correlation (DIC) addresses the hazardous effects caused by the changes of speckle on the surface of any object measured using DIC, which undermines most of the prejudice with regards to displacements and strain calculations. Such factors range from types of materials undergoing deformation, deformation rates themselves and to the imaging conditions applied.This topic allows to gain an understanding of the basic concepts of DIC and speckle pattern analysis as well as the normalization of measurement accuracy loss caused by speckle deformation. Advanced DIC techniques, such as multi-scale, adaptive subset size, 3D, and dynamic DIC, are presented as solutions to overcome speckle deformability limitations. Those working, studying or researching such areas as materials engineering, mechanical engineering, biomechanics, aerospace, automotive and biomedical is encouraged in this field. The aim is also to promote dialogue on the strategies of reducing risk factors and the successful application of techniques, as well as on the scope of research which should follow regarding a continued improvement of DIC measurements. This will enable the scientific community concerned DIC measurements of various materials to achieve higher resolution and minimized errors in DIC measurement techniques.

***Keywords* – Digital Image Correlation , Speckle Deformability , Speckle Pattern , Effects and Mitigation Strategies.**

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I. INTRODUCTION

Digital Image Correlation (DIC) has become one of the leading innovations in the field of non-invasive techniques for measuring surface displacement and strain and has found its applications in several areas including but not limited to, structural health monitoring, material testing, biomechanics, and quality assurance. Within short span of time, DIC has emerged as a preferred measurement technique among the researchers and practitioners across the globe because it does not involve the prohibitively expensive yet imprecise contact or laser scanning methods and offers high resolution measurement of surface displacements over a large area, the so called full field measurements.

However, speckle deformability is one phenomenon that significantly compromises the accuracy and the reliability of DIC measurements. This is the phenomenon in which there are changes in the characteristics of the speckle patterns created by the surface of interest as a result of the applied strain or change in environmental condition. Such speckle patterns which are achieved by applying a random texture to the surface of interest are crucial for making DIC measurements. Any deformation in such patterns leads to a distortion in measurements taken hence the distortion leads to erroneous interpretations.

The effects inherent to speckle deformability on DIC are not only are not only structural but also dynamic. Using structural health monitoring example, such speckle deformability causes false or missed defects posing danger to such monitored critical infrastructure. In material testing, for instance, where inaccuracy in measurement may lead to misrepresentation of material properties, this will hinder the successful design and manufacture of advanced materials. In spatiotemporal acquisition of soft tissue deformation in measurement based diagnostics, speckle deformability damages the quality of these measurements leading to potential wrong diagnostics or treatments.

So far, the last few decades, a lot of advances have been made in terms of how the relationships between speckle deformability and applications can be understood and additional measures developed to curtail these effects. For instance, advanced DIC algorithms, high-resolution imaging systems, and optimized literature patterns have enhanced the accuracy and reliability of measurements.

II. RELATED WORKS

Liu et al. [1] Digital Image Correlation (DIC) relies on capturing deformation by tracking changes in speckle patterns across images. Since DIC outcomes are sensitive to the quality and characteristics of these patterns, the accuracy of deformation measurements is directly influenced by factors like pattern intensity and contrast, distribution, and scale.raditionally, assessments of speckle pattern quality focus on single parameters, such as the Mean Intensity Gradient (MIG). MIG is widely used because it is straightforward and effective for estimating standard deviation error, reflecting pattern consistency across images. However, MIG does not capture the full scope of error in DIC measurements, particularly for mean bias error. Mean bias error emerges from complex, often directional, deviations in the pattern, influenced by higher-order intensity gradients which MIG alone cannot address.Mean bias error in DIC corresponds to systematic errors that affect overall measurement accuracy. It is sensitive to the first-order and second-order gradients in the speckle pattern, which affect how well the DIC algorithm can recognize and match pattern points.To address this gap, researchers developed a new parameter, *E*f.which is based on mean bias error principles and reflects the influence of higher-order gradients.Ef is designed to evaluate speckle pattern quality specifically from the perspective of mean bias error. This makes it a complementary metric to MIG, which continues to be useful for assessing standard deviation error. By combining both *E*f and MIG, a more comprehensive evaluation of speckle quality is possible, covering both systematic and random error aspects.

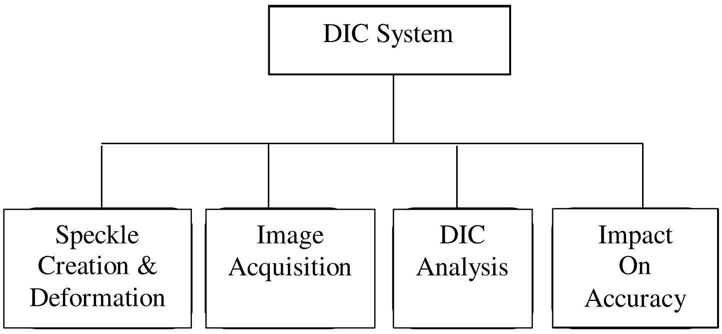
Kiran et al. [2] said that Digital Image Correlation (DIC) is an optical, non-contact measurement technique used extensively for deformation, stress, and strain analysis in materials science. In aerospace, DIC offers promising applications for the structural health monitoring (SHM) of aircraft components due to its ability to detect precise deformations and strain distributions. DIC involves three main stages: image acquisition, processing, and DIC analysis. Images of the speckled surface are captured pre- and post-deformation, with specialized software analyzing the differences to produce stress and strain contours. This method provides crucial insights into material behavior under varying conditions, enhancing safety and efficiency in aerospace applications.
DIC helps study strain uniformity, crack progression, damage in composites, high-temperature strain, and vibrational response. It also enables real-time tracking of wing vibrations for flutter analysis, identifying critical areas that may require maintenance.Parameters like Mean Intensity Gradient (MIG) and techniques like Iterative Least Squares (ILS) and Newton-Raphson algorithms play critical roles in DIC's precision and reliability, especially in monitoring complex, high-stress components like wings.

Sadowski et al. [3] investigates the influence of speckle pattern characteristics on the accuracy of strain measurements obtained using Digital Image Correlation (DIC). DIC is a widely used optical method for full-field strain analysis, relying on the tracking of a speckle pattern applied to a surface during deformation. The study specifically examines how the deformability of the speckle pattern itself—i.e., the ability of the speckles to undergo distortion along with the material surface—affects the quality and reliability of the strain measurements. The authors emphasize that the speckle pattern should deform in a manner similar to the material surface to ensure accurate strain data, but deformations in the speckles can lead to measurement errors if they do not behave accordingly.The research presents experimental findings where different speckle patterns, with varying deformability characteristics, are tested under different loading conditions. The results indicate that poorly deforming speckle patterns can introduce significant errors in strain measurements, particularly in regions of high deformation. The study also provides recommendations for optimizing the speckle pattern design, including using high-contrast materials with appropriate stiffness and adhesive properties to minimize discrepancies between the speckles and the material. By understanding the role of speckle deformability, the paper contributes to improving the precision and reliability of DIC-based strain measurements, thereby advancing the technique's application in materials testing and structural analysis.

Jackson, et al. [4] explores how the deformability of speckle patterns impacts the accuracy of Digital Image Correlation (DIC) in biomechanical applications. DIC is a powerful optical technique used to measure full-field displacements and strains in materials and biological tissues. In biomechanics, DIC is applied to study complex deformations in soft tissues, such as muscles, skin, and ligaments. However, the performance of DIC can be compromised if the speckle pattern does not deform in a manner that accurately reflects the tissue deformation. This study investigates how variations in speckle deformability—due to the characteristics of the speckle material, application method, and tissue properties—can lead to errors in displacement and strain measurement, potentially affecting the reliability of biomechanical analyses.The authors conduct experiments using different types of speckle patterns on soft biological tissues under various loading conditions. They observe that a mismatch between the deformability of the speckle and the tissue can lead to errors in strain measurements, particularly in tissues undergoing large, non-uniform deformations. The study highlights that, for accurate biomechanical analysis, the speckle pattern must closely mimic the tissue's deformation behavior. Additionally, the paper discusses methods to improve speckle application, such as selecting more compliant speckle materials or optimizing the application process to ensure better correlation with tissue movements. Overall, the research contributes valuable insights into enhancing DIC's precision for biomechanical studies, emphasizing the need for careful consideration of speckle properties when applying the technique to biological tissues.

Joseph et al. [5] focuses on understanding how speckle distortion influences the accuracy of Digital Image Correlation (DIC) when applied to biomechanical systems. DIC is commonly used for measuring displacement and strain in biological tissues, but its effectiveness can be compromised if the speckle pattern used to track surface deformation becomes distorted during the process. The study develops a computational model to simulate the effect of speckle distortion, considering various factors such as tissue properties, the type of deformation, and the speckle pattern's material characteristics. By quantifying how distortions in speckle geometry affect the correlation accuracy, the study seeks to better understand the limitations of DIC in biomechanics.Through simulations and experimental validation, the study finds that distortions in the speckle pattern—whether due to material mismatch, improper speckle application, or high tissue deformation—can lead to significant measurement errors, especially in regions experiencing complex, non-uniform deformations. The paper also examines the relationship between different distortion types (e.g., stretching, shear) and the resulting strain measurement errors. The authors propose potential solutions to mitigate these effects, such as improving the design of the speckle patterns, adjusting imaging settings, or incorporating advanced correction algorithms. This research contributes to enhancing the reliability of DIC in biomechanical applications by providing a more comprehensive understanding of the role that speckle distortion plays in the measurement process.

III . DISCUSSIONS



Digital Image Correlation (DIC) is a surface distortion and strain measurement technique that uses high-speckle density patterns on the surface of subjects in motion to relate the change in position of the surface texture. Moreover, one or several cameras are used to capture the images of the objects before the loads and during application of the loads. The first stage of the process involves the deposition of random but high-contrast features termed “speckles” on the surface of the object being tested. Such deformation causes a shift of the above features. . DIC software analyzes consecutive images, dividing them into smaller subsets (correlation windows) to detect surface distortion. Surface preparation consists of the application of intentional surface treatments - in particular random high-contrast patterns usually referred to as speckles. Under applied load, as the specimen deforms, so too do the speckle patterns. The DIC algorithm divides the images into small subsets (also called correlation windows) and looks for the best matching correspondence between the regions in two consecutive images. DIC, on the other hand, allows resolution of material behaviour under distinct loads and different treatments by monitoring stretch of the silicate pattern.

The accuracy of DIC measurements is significantly influenced by the design of the speckle pattern. The resolution of the stain measurements is high due to the degree and dimension of the speckles.On the contrary however, if the speckles are too small they may be indistinguishable while if they are too big they lower the spatial resolution. For DIC applications, uniform random patterns of speckles provide the best configuration as they reduce correlation incertitude. Commonly, square or circular speckles are used, nonetheless their noise performance is not intact as the angle and shape tends to matter. For example, square speckles can contribute to strain measuring errors in scanning electron microscope (SEM) based digital image correlation (DIC) analysis because they noisily patterned along the scanning direction. Changing the position of the square marks, an unwanted orientation that elicits such noise can be avoided. In elastic DIC, concept conditioning effects mandate that the speckles should not deform otherwise tracking becomes a problem. However, high strain or large deformation studies change this ability to track speckles, as they become deformed causing errors in DIC processing. Therefore, the deformability of speckles is an important factor to take into account, mainly in dynamic or high-stress situations, where such patterns can be highly distorted. Optimal design often means that speckles are stiff enough to avoid deformation when imaging but also capable of remaining to the surface during testing. Methods such as spray painting, inkjet printing and photolithography are the standard approaches followed to elaborate speckle patterns.Smaller subsets improve spatial enhancement due to over the limit subset shrinkage but risk high noise level especially where there is variation of the speckle pattern owing to speckle deformation at different loading stages.

In an absolutely controlled environment, speckle patterns can be expected to remain rigid markers in shape and dimension during any deformation process. On the other hand, speckle deformability in Digital Image Correlation (DIC) refers to the change in an internal speckle pattern due to the changes in strain which affects measurement results negatively.Particularly, speckles are important to DIC software in surface displacement and strain tracking, and the surface displacements are compromised when the speckles deform. An approach that may help to solve this problem is the speckle pattern optimization with a focus on the distribution, shape, and also the material of the patterns, which will yield more precise and better-anchored DIC readings.This is particularly important in high-strain applications where large deformations may result in some change in the characteristics of the speckles rendering DIC software ineffective in tracking changes in surface displacements and strains. Speckles are key reference markers in DIC and any changes in their structure affect tracking precision and in turn elevate noise in the measurements. High density speckle patterns consisting of small and randomly dispersed dots are usually more resistant to slight changes in form, however with extreme conditions of loading such as very high temperature or excessive strain in practice, the pattern may still be destroyed. To reduce such influences, it is possible to use a such method, like optimization of speckle patterns with respect to density, shape, and material composition, so that deformations do not significantly affect measurement results, make.

DIC measurements may be affected by several error sources due to speckle deformability and other factors. Digital Image Correlation (DIC) is accompanied with a number of error mechanisms which affect the measurement accuracy, precision and reliability of displacement and strain data. The main contributing factors are the changes in lighting and imaging conditions, which as a result produce some noise that affects correlation algorithms. DIC also suffers from even more limitations because of its quality or deformability of a speckle such as during high deformation condition where in most cases speckles tend to elongate, smear or even get disintegrated. Noise produced by the imaging apparatus or surrounding area degrades the measurement quality while measuring subsets increases noise levels while improving spatial resolution. More so, a DIC system when applied to three-dimensional studies or in the tracking of complex surfaces displacement involving the DIC, suffers from the out-of-plane displacement as well as depth of field error. Image distortion because of lens distortion and calibration error also result to measurement inaccuracy through the distortion of image geometry. Imaging modal noise and resolution limits of the imaging pixels determine the minimal displacement that can be detected reliably. These types of errors can be reduced by designing suitable geometries of the speckle patterns, taking into consideration the surrounding conditions, improving the camera resolution and improving the calibration process. These measures should increase the credibility of DIC measurements especially for the applications such as structural health monitoring, material testing and biomechanics where high precision is required. For instance, advanced design of speckle patterns, more sophisticated correlation algorithms that can accommodate large non-linear deformations and out-of-plane movements with multi-camera systems are necessary to reduce these errors.

Speckle patterns are random,which is a high-contrast distortion in the image intensity due to interference of a number of light waves. In the practice of Digital Image Correlation (DIC), instead of random dots painted on the surface of interest, a speckle pattern is textured on the surface of interest by different means such as spraying, painting or stickering and so on. The parameters of the speckle pattern play a vital role in the precision of DIC. In DIC imaging techniques, the ideal speckle was high in contrast, uniform in density and size distribution. The speckle size however should be big enough to enhance the spatial resolution without introducing noise into the image. Also the speckle pattern should be isotropic and homogeneous for proper measurement in all directions Digital Image Correlation algorithms operate on the principle of deformation of speckle patterns in images taken at different times. The subset based method is the widely used DIC technique, which decomposes the image in the smaller areas, the so-called subsets, and computes the shift of each of these subsets. This technique ensures very high resolution and accuracy of measurements, however it is affected by the change in the shape of the speckle patterns. Other DIC techniques are the feature based tracking, which follows certain features in the image, and machine learning techniques that recognize the patterns in the images. Subset based methods can be further classified into two sub-categories: (1) standard subset based approach and (2) improved subset based procedure. The traditional approach involves the use of subsets of constant size, while the approach that is modified is able to enlarge or reduce the size of subsets proportional to the amount of change in shape that the region endures. For the experiments, high quality pictures were taken using a digital camera that was mounted and focused on lenses to bring clarity in the images, led panels which were arranged in a particular way so that they provided enough light without harsh shadows or reflections, and a test object with a distinct speckle pattern applied on it. Random spray painting technique was used in designing the speckle pattern.

The impact of speckle shape variations on the accuracy of Digital Image Correlation (DIC) is rather expansive, giving rise to various decorrelation error sources – displacement error, strain error, spatial resolution cutoff, noise exacerbation, subset size restriction, material property error, and limited ranges of measurements. Ruined speckle patterns propagate in such a way that detracts from the correlation of images, and as such measurement capabilities suffer, so too do the calculations of displacements which in turn create issues with the evaluation of strain or stress. Furthermore, it is clear that having deformed speckles also reduces the minimum displacement that can be measured, which in turn, affects the level spacing resolution and increases measurement uncertainty. The same is true for the accuracy of other material properties, elastic, plastic, or viscoelastic materials, all of which suffer under the errors introduced by the deformability of speckles. The effects of speckle deformability are also influenced by certain factors such as; the type of material, impose deformation rates, quality of the speckle pattern, recording conditions, and DIC algorithm settings.DIC methods may also be used along with other techniques to assess the measurements made. When limits on speckle deformation are understood and dealt with, it becomes possible to make DIC measurements more precise and more trustable which can be used to characterize material behavior or allow structural health monitoring with confidence.

Understanding the factors that influence speckle deformability when working with Digital Image Correlation DIC is both complex and interrelated, subsequently influencing how accurate and dependable the measurements will be. To elaborate, Digital Image Correlation is a non-contact optical technique that is designed to measure the displacements and strains on the surface of materials. This indicates that speckle deformability, that is the effect of change in the characteristics of the speckle pattern as a result of strain or other environmental factors, has a direct effect on DIC. More complex factors that define the speckle deformation do include but not limited to the elasticity, plasticity, viscoelasticity, anisotropy, grain size and texture of the given material all contribute to the effect of speckle deformability. When it comes to elastic materials, they can be reshaped to the original forms while plastic ones change the shapes and so retain permanent deformation altering the speckle patterns. Also, for viscoelastic materials, deformations do not only occur but they also occur dependent on time, which makes the accuracy of taking measurements difficult.

Characterictics of a speckle pattern such as size, number of speckles, speckle contrast, the arrangement of speckles as well as the overall shape of a speckle pattern will also play an integral role in how a deformed image will appear, In this case, small-sized speckles are easily lost in the noise while large-sized speckles do not resolve well enough to accurately measure strain. A reasonably high density patterned speckles that has high contrast are beneficial to DIC technology but can also cause losses of correlation when this pattern undergoes deformation. DIC works best with random arranged 'dots' which are in a circular form. Imaging geometry including factors such as the camera resolution, not keeping the lens axis perfectly straight, the amount of light, the angle and noise in the picture are all very important for preventing artifacts in the speckles. In most cases for instance, the higher the resolution of the camera used the better the tracking of smaller speckles that would be lost in a lower resolution screen, however the higher resolution introduces quantization noise. In addition, lens distortion changes the position of the speckles thereby introducing position errors.

Some of the deformation parameters such as strain rate, load level, load angle and temperature influence the degree to which speckles can deform. For instance at higher strain rates, the speckle patterns are either stretched or blurred at a rate that is quicker than what the DIC software can keep up with, hence the accuracy of the imaging system is compromised. Color of speckle patterns changes with the load direction not only because of deformation of the blur patterns but also because of reorientation of scattering centers within the surface.

The steadiness of speckle patterns is important for DIC purposes and measurements. Lack of adherence of a pattern leads to decorrelation and error, while any elastic distortion of a pattern on a soft substrate introduces an error into measurement. Such parameters as temperature, humidity, and even chemical exposure will affect the stability of a pattern. Most of the time, unstable patterns will lead to loss of correlation hence increase in measurement error rates. Other relevant material parameters such as smoothness and reflectivity of the surface make the application of speckle pattern difficult. How elastic a material is as well as the strain capacity also assist in the stability of the pattern and DIC74004619 com materials deform differently which makes them difficult to use for DIC measurements. The stability of speckle patterns is essential if the DIC data is to be reliable. Environmental or material interactions that result in deterioration or variation of the pattern will adversely affect measurements. Measurement example, variations in temperature can cause expansion or contraction of the speckle pattern thus changing its form. Likewise, the presence of moisture or chemical agents may cause the pattern to weaken its mechanical bond or change the optical characteristics of the pattern. Materials also create limitations when carrying out DIC measurements. The smoothness and reflectivity of a surface affect the application of a speckle pattern, and the elasticity of a material and the strain capacity of the material affect the stability of the pattern. In composite materials, especially, DIC measurements are further complicated by their non-uniform deformation. In addition, due to the intricate microstructure of composite materials, there may be internal distortions making it hard to keep the speckle pattern unchanged. Challenges with software and algorithms similarly restrict DIC performance. Size of subset and step is important to DIC accuracy, interpolation and correlation criteria guarantee the precision. Measurement quality is also affected by whiting and suppressing techniques.

The optimization of speckle patterns is an important aspect for reliable DIC tracking. To this end, the size of speckle patterns is recommended to be between three to five pixels and with high background contrast. Adhesives are preferred for use on bendable materials. There are several ways of creating optimal patterns, such as spray painting in a controlled manner, stencils, screen printing, adhesive films inkjet printed, and so on. Better accuracy is achieved in measurements with the help of advanced DIC techniques. The multi-scale DIC technique combines images of both high resolution and low resolution to consider both local deformation and global deformation respectively. Seamless adaptation of measurement conditions with changing deformation is achieved in adaptive subset size selection that is suitable for measurement high accuracy. Out of properties developed in 3D and stereo DIC is the capacity to measure the out of plane displacements. On the work of cameras, dynamic DIC us utilized for capturing rapid changes in structure composed of advanced materials. Efficient material preparation is also necessary for success. Degreasing and application of primer on surfaces promote better speckle saturation helping to mitigate errors. Roughening of surfaces enhances sticking properties and decreases shiny surfaces, thereby improving the definition of the patterns. Stretchable adhesive sheets are intended for use together with elastic bodies; however, low-stress application techniques are used to avoid damaging components.

IV.CONCLUSION

The study of speckle deformability's impact on DIC helps in understanding the significance of speckle deformability while using DIC allows one to appreciate the importance of precision measurement for the complex deformation analysis. The quality of a speckle pattern factors such as the density, shape and arrangement directly affects the measurement of strain fields through the use of DIC technology especially in high performance scanning electron microscope (SEM) and other high resolution applications. In addition, high-density and well-defined speckle patterns improve correlation accuracy and reduce signal noise whereas avoiding the alignment of speckles with the raster scan direction reduces directional strain noise in the SEM. Strain intensity noise is also an important factor when conducting SCMDA to both balance the subset size and the speckle density in order to optimize the spatial resolution. This allows for better speckle optimization and DIC tailoring depending on the testing conditions and materials to be used. Therefore the developments in DIC methods with improvement in the speckle pattern used enables reliable strain evaluation in many fields such as aerospace and materials due to the non-invasive full field assessment that is required in structural health monitoring and investigating of high temperature materials.

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