

# Detection of Cracks and Busbars Failures in Solar Cells by Moiré Pattern and Laser Speckle Techniques

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*Received: 15<sup>th</sup> March 2025; accepted: 9<sup>th</sup> July 2025*

This study investigate the detection of mechanical faults in solar cell busbars, caused by shock wave-induced vibrations, using Moiré pattern analysis followed by laser speckle shearography. The busbars, critical for transferring electrical output, are susceptible to structural damage from vibrations, which can degrade their performance. Moiré pattern analysis is used to identify early deformations and strain, while speckle shearography is employed to provide high-resolution detection of strain changes over time. Regular grids are overlaid on the panel surface to capture Moiré fringes in the early stages of vibration, transitioning to speckle variations for more detailed strain mapping. Failure-prone areas are effectively located by this method, enabling early detection of busbar failure. Advanced optical techniques are integrated to improve fault assessment, extend solar panel lifespan, and enhance durability in photovoltaic applications.

**Keywords:** Solar cell, Defects, Busbars faults, Moire pattern, Deformation, Shearography

## 1 Introduction

Solar cells are essential in photovoltaics to transform sunlight into electricity. However, their performance in busbars, which conduct current between solar cell modules and external circuits, can be affected by mechanical damage. Moiré pattern analysis is employed to detect large-scale deformation, reveal mechanical stresses from shock or vibrations, and identify busbar failure-prone areas<sup>1, 2</sup>. Dynamic tremor-induced shakings are applied to solar cells, and Moiré patterns are captured to analyse strain distribution, emphasising regions at risk of busbar disconnections<sup>3, 4</sup>. Moiré interferometry is used to assess deformation under dynamic loading, particularly in detecting micro-fractures in busbar connections<sup>5, 6</sup>. Surface strain in solar panels is quantified using Moiré patterns, focusing on stress points leading to failure<sup>7, 8</sup>. Deformation in solar panels is monitored using Moiré techniques, and mechanical issues in busbars caused by shock-induced vibrations are identified<sup>9, 10</sup>.

The structural integrity of solar panels is evaluated through Moiré pattern analysis, measuring deformation caused by shock-induced vibrations and revealing potential vulnerabilities<sup>11, 12</sup>. Shock or impact forces are propagated through materials,

causing local strain, displacement, or cracking. Busbars, being particularly susceptible, are prone to mechanical failure under shock-induced stress<sup>13, 14</sup>. The mechanical stress in photovoltaic modules is monitored through Moiré analysis, enabling early detection of busbars failures<sup>15, 16</sup>. These failures are not detected by traditional inspection methods and can lead to performance degradation<sup>17</sup>. Early detection through non-destructive fault detection methods ensures long-term reliability<sup>18</sup>. The ability of Moiré patterns to identify minor deformations in busbars under shock-induced vibrations facilitates early fault detection<sup>19</sup>. The technique is applied to create strain maps of photovoltaic systems under shock waves, with regions at risk of busbar disconnections being identified<sup>20</sup>. Strain and displacement in solar panels under mechanical loading are measured through Moiré analysis, providing insights into their structural behaviour<sup>21</sup>. The vibrational response of solar cells is assessed, allowing the detection of mechanical failure regions around busbars<sup>22</sup>. Through Moiré pattern imaging, surface deformations in solar cells are analysed, aiding in the identification of busbar failures before electrical performance is affected<sup>23</sup>. Mechanical stresses in solar panels from dynamic forces are investigated, helping locate high-risk areas for busbar failure<sup>24</sup>.

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To improve the accuracy of deformation detection, laser speckle interferometry is combined with digital image correlation, enhancing the evaluation of surface deformations in photovoltaic modules under mechanical stress<sup>25</sup>. Shearography is used to detect micro-fractures in photovoltaic cells, highlighting its effectiveness in identifying potential failures and enhancing the reliability of solar energy systems<sup>26</sup>. Continuous monitoring of solar cell performance and structural integrity is facilitated by this technique under varying environmental conditions<sup>27</sup>. Microstructural deformations in solar cell busbars, which are critical to photovoltaic system reliability, are detected through laser speckle imaging<sup>28</sup>. Mechanical deformations in photovoltaic modules under shock loading are observed through laser speckle interferometry, providing insights into module durability under real-world stress conditions<sup>29</sup>. A non-destructive laser speckle-based method is employed to detect micro-cracks in solar cells, ensuring long-term reliability and preventing performance degradation<sup>30</sup>. Stress analysis of solar panels is improved using laser speckle interferometry, with advanced data processing techniques enhancing deformation measurement accuracy<sup>31</sup>.

Moiré pattern analysis is used to detect electrical issues in busbar and finger defects generated by the simulation of shock-induced vibrations in the sample at an earlier stage, and then shearography is used to detect large deformations in the solar cells.

## 2 Materials and Methods

Moiré pattern analysis is employed as a non-destructive optical technique for measuring strain, displacement, and deformation in materials. Two regular grids, either transparent or projected, are overlaid onto a deformed surface to create Moiré patterns. As deformation occurs, the Moiré fringes shift due to the displacement between the grids. These distortions are analysed to measure changes in the shape or movement of the surface. A fine grid pattern, typically as a transparent film or printed grid, is prepared and overlaid onto the solar cell or busbar surface. The grid is carefully aligned, and a laser or digital projector is used for projection. A shock wave or vibration is applied to the solar cell, causing surface deformation, which, in turn, deforms the overlaid Moiré grid. This process is similar to laser speckle interferometry.

As the surface deforms, the two grids shift relative to one another, forming Moiré fringes that appear as

interference patterns. These fringes indicate surface displacement, and their shape and number change with increasing deformation. A camera or optical sensor captures the Moiré pattern in real time as the shock or vibration is applied. The changes in Moiré fringes are recorded, providing a visual representation of the deformation.

The process of simulating and measuring deformation in a grating system begins with the generation of an original grating pattern, which serves as the reference. A deformation is introduced by applying a sinusoidal or linear displacement along a chosen direction, typically with a peak amplitude of 0.5 cm. This deformation is represented by a variable that shifts the grating accordingly. Once the deformation is applied, the difference between the original and deformed gratings is calculated, leading to the generation of a Moiré pattern by subtracting the deformed grating from the original. The Moiré fringes are formed as a result of the interference caused by the deformation and are analysed to determine the magnitude of the displacement.

The spacing of the Moiré fringes is inversely related to the deformation, and by studying the intensity fluctuations along a central line of the Moiré pattern, the magnitude of the deformation can be estimated. Various visualisations are produced, including the original grating (undisturbed pattern), the deformed grating (simulated displacement), the Moiré pattern (resulting interference), and the deformation profile (quantitative measure based on intensity variations). This method offers a non-destructive approach to analysing mechanical strain and deformation in a grating system, making it a valuable tool for evaluating structural integrity.

## 3. Results and Discussion

### 3.1 Moiré Pattern for the Defect Study

The busbars in solar cells are essential for transporting electrical output, and any mechanical damage, such as cracking or detachment, can significantly reduce their efficiency or result in complete failure. Mechanical stresses from environmental factors or improper handling, such as shock waves or vibrations, can damage the busbars and disrupt the electrical circuit of the solar cell.

To model a typical solar cell, a size of 156mm × 156mm is set, with an image resolution of 500 pixels and three busbars, each 2mm wide, evenly spaced along the X-axis in a periodic grid pattern. A 2D grid is created to represent the surface of the solar cell,

with the X and Y axes defining the physical dimensions, while the image is visualised in pixels. The busbars are modelled as a rectangular pattern, where 1s (white) represent the busbars and 0s (black) represent the rest of the surface.

The busbar positions along the X-axis are iterated, and each busbar is assigned a fixed width, filling the occupied space with 1s. The sinusoidal deformation is applied to the busbar pattern, occurring along the Y-direction as a sine wave with a peak amplitude of 5mm. This adjustment alters the Y-positions of the busbars based on their X-coordinates, simulating the effects of mechanical deformation or bending caused by external forces.

As a result, the busbars, initially straight, appear wavy, creating a deformed pattern that reflects the physical stress on the solar cell. The Moiré pattern is generated from the interference between the original, undeformed busbars pattern and the deformed pattern. Moiré fringes appear as a visual effect when two regular patterns slightly overlap, creating new interference patterns that reveal subtle alignment variations between the two grids.

The Moiré pattern is computed by taking the absolute difference between the original and deformed busbars patterns. Moiré pattern analysis is used to detect small deformations by overlaying two regular grids, one on the material surface and one as a reference. When the surface deforms, the grids shift, creating interference fringes that can be analysed to measure strain. This technique is effective in identifying stress regions in solar cells around the busbars. Issues such as loosening or micro-fractures can be detected early, preventing potential failures. Fig. 1 shows the deformation of the sample cell busbars in the X-direction.

The deformation of the solar specimen busbars and the corresponding Moiré pattern analysis in the Y-direction are displayed in Fig. 2 and the random directional displacement of the busbars is illustrated in Fig. 3.

To analyse the deformation, the Fast Fourier Transform (FFT) is applied to the displacement data, converting the time-domain signal into the frequency domain. This transformation helps identify dominant vibration frequencies and provides insight into the relationship between vibration frequencies and their intensities. The frequency spectrum is plotted to visually represent these variations, and the frequency data is averaged over specific intervals for improved

clarity. This averaging process helps reveal patterns that may not be immediately apparent in the raw data.

By examining both time-domain and frequency-domain representations of vibration data, a comprehensive understanding of temporal vibration behaviour and the underlying frequency components contributing to surface motion is achieved. This technique offers precise, non-destructive vibration analysis, using video data and advanced signal processing methods to study vibrations in materials, mechanical structures, and dynamic systems. The disappearance or disconnection of the sample busbars and fingers through Moiré analysis is illustrated in Fig. 4.

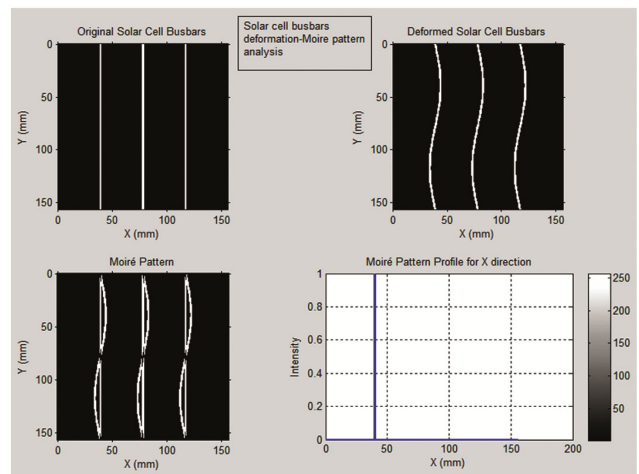


Fig. 1 — Solar cell busbar deformation - Moiré pattern analysis (X-direction)

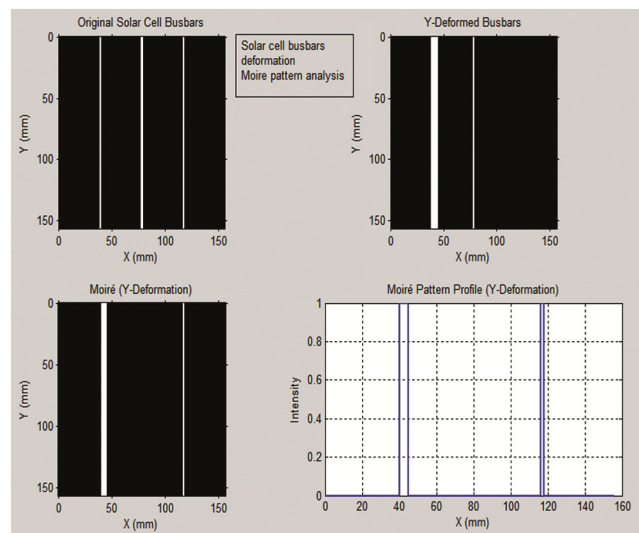


Fig. 2 — Solar cell busbar deformation - Moiré pattern analysis (Y-direction)

To prevent cracking and disconnections in solar panels, materials with high fatigue resistance should be used, and robust soldering techniques must be ensured. Proper mounting is crucial, with panels being securely fixed to minimise vibration or tremors, especially in systems subjected to movement, such as tracking mounts.

In areas prone to seismic activity or strong wind loads, seismic-resistant designs should be incorporated to help panels withstand vibrations. These preventive measures can significantly reduce the risk of mechanical failure and enhance the overall durability of solar installations. The speckle image (radial displaced with tilt) and sample image

(subtracted from an unsheared image) are shown in Fig 5 and 6, respectively. The profile for the solar sample with busbars and fingers is as shown in Fig. 7.

**3.2 Laser Speckle Vibration Analysis**

Speckle vibration analysis is employed to examine and visualise dynamic vibrations in a material or surface by analysing speckle patterns captured in video recordings. This process integrates image processing and signal analysis techniques to accurately measure and interpret vibrations over time. A video of the vibrating surface is loaded, allowing for frame-by-frame analysis, where individual frames are examined to assess changes in the speckle pattern. Fourier analysis is then applied to identify the dominant vibration frequencies and track displacement

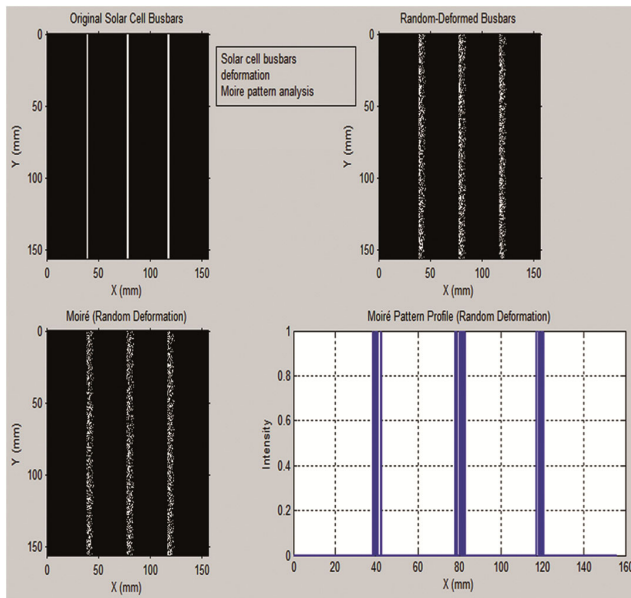


Fig. 3 — Solar cell busbar deformation - Moire pattern analysis (Random-direction)

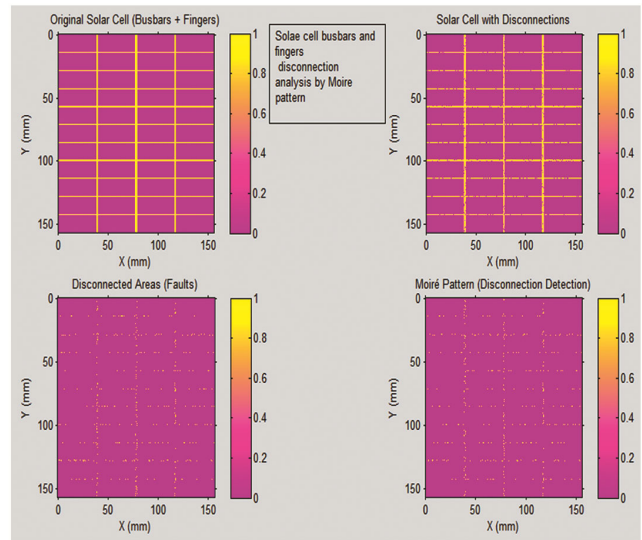


Fig. 4 — Solar cell busbars and finger disconnections by Moire pattern analysis

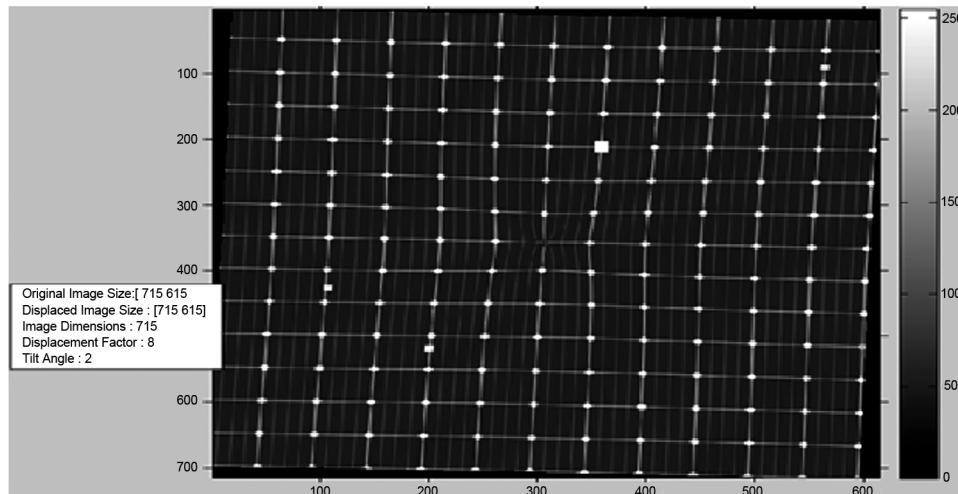


Fig. 5 — Sample shearing image pattern

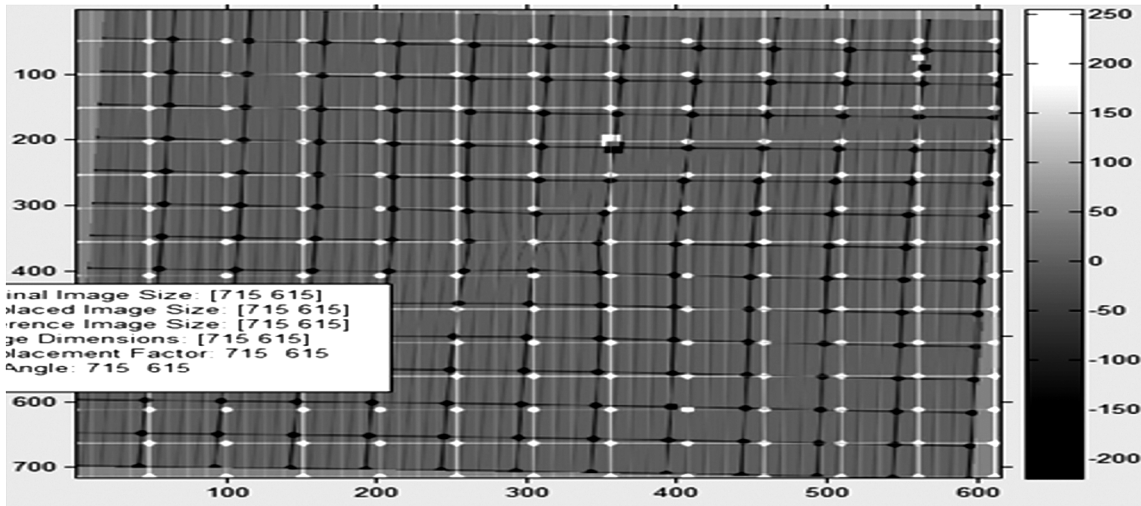


Fig. 6 –the shearing sample was subtracted from an un-sheared image

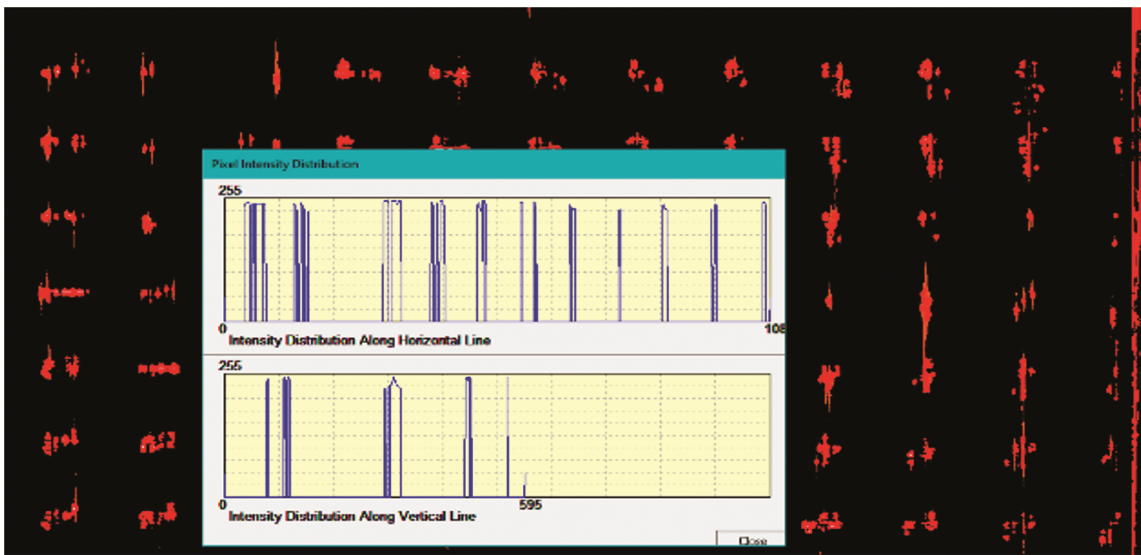


Fig. 7 — Profile for the solar sample with busbars and fingers

variations. The video serves as a primary data source, capturing the speckle pattern on the surface shifts due to vibrations. By comparing consecutive frames, the displacement of the speckle is calculated and represents the motion of the surface. The displacement values are plotted over time, generating a waveform illustrating the evolution of vibration dynamics. The dynamic speckle vibration frame captured at the initial stage is depicted in Fig. 8, and the final stage is shown in Fig. 9.

Shock or impact forces are propagated through the solar cell, inducing vibrations that cause local strain, displacement, or cracking. Since the busbars are stiffer than the solar cell substrate, they are especially vulnerable to these shocks. Repetitive or significant

shock-induced vibrations lead to a weakening of the structural integrity of the solar cell and damage to the interconnection system.

Early detection is considered crucial for preventing long-term failures. The amplitude of vibration increases with higher external forces and can lead to bending or cracking if the vibration persists or exceeds the mechanical limits of the components. Stress induced by vibration is related to the force applied to the material and its cross-sectional area. Over time, repeated vibrations cause fatigue in the metal fingers and busbars, resulting in cracks or fractures. If the material's fatigue limit is exceeded, the connection between the fingers and busbars may break.

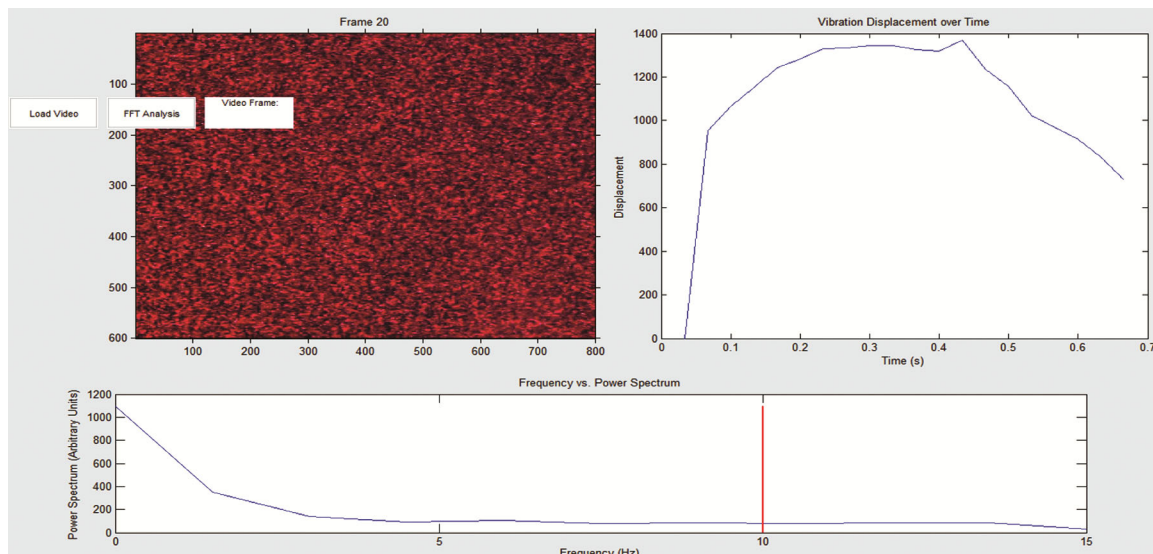


Fig. 8 — Dynamic speckle vibration at an initial level

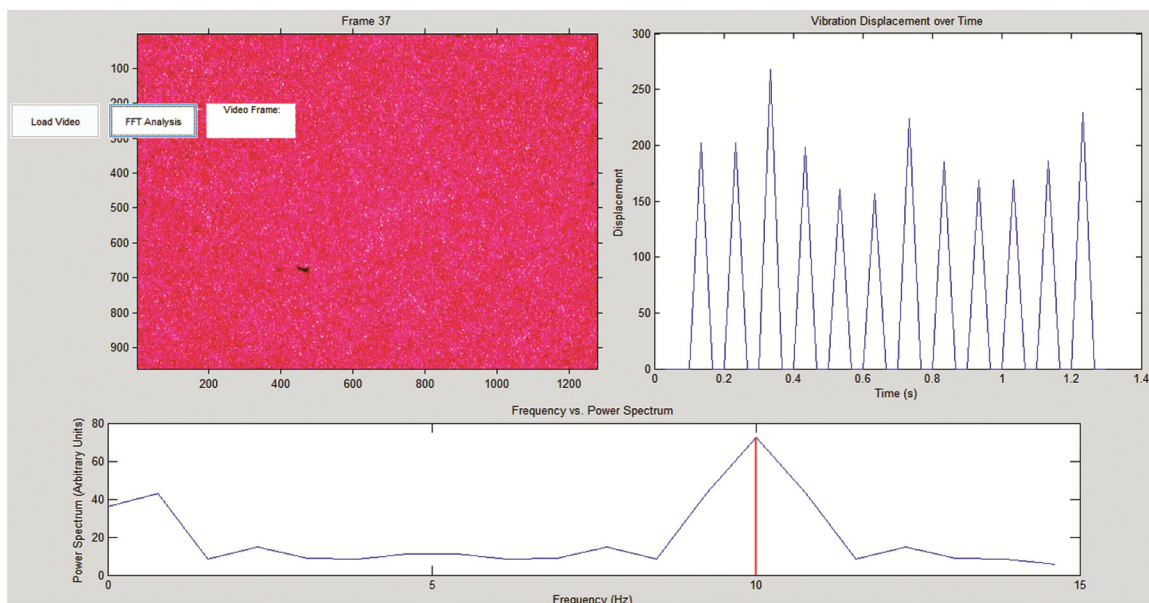


Fig. 9 — Dynamic speckle vibration at maximum level

Vibration amplitudes that are too large can deform the busbars and fingers, leading to disconnections. Low-frequency vibrations (10-100 Hz) cause minor deformations in the solar cell structure, leading to stress on solder joints and connections between the fingers and busbars over time. High-frequency vibrations (100 Hz - 1 kHz+) can cause immediate mechanical failure, especially when pre-existing micro-cracks or weak solder joints are present. Fingers, typically 0.1 to 0.3 mm wide, can bend or break under vibration-induced stresses if forces exceed their strength. Busbars, ranging from 0.5 to

1.0 mm thick, may lose contact with the solar cell if vibrations are too strong or soldering is improper, potentially impacting electrical resistance and reducing panel efficiency.

### 3.3 Laser speckle technique (Shearography)

A laser beam with a wavelength of 540 nm and a power of 1 mW illuminates the object. A CCD camera, combined with a Michelson interferometer, captures the sheared images. The mirror-1 in the interferometer allows the shear direction and amount to be adjusted by tilting mirror-1; the speckle pattern

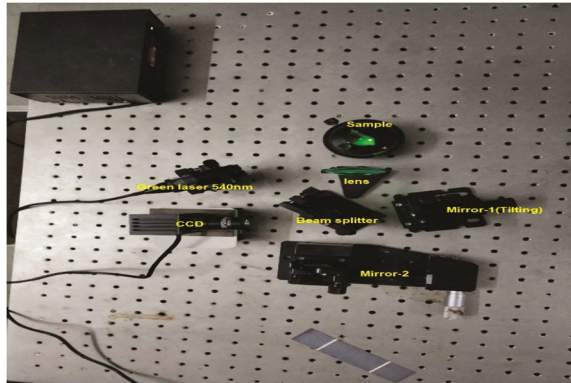


Fig. 10 — Experimental setup for shearography

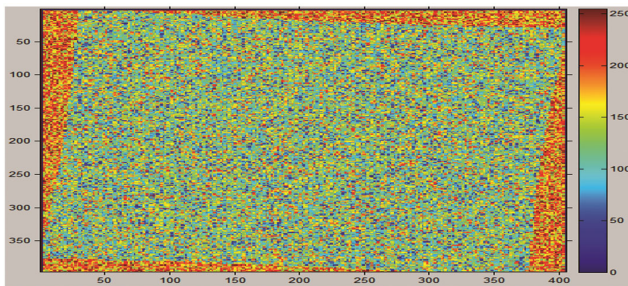


Fig. 11 — Overlaying the original and shearing images

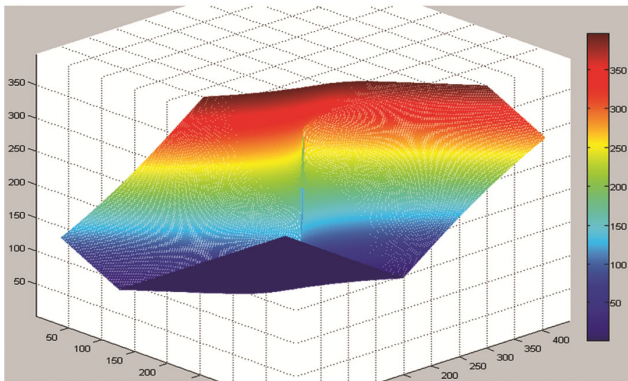


Fig. 12 — Shearogram (First derivative of deformation)

data is processed by the computer with the help of a CCD, as shown in Fig. 10.

The overlay of the original image and the sheared image of the solar sample (taken on the backside) is displayed in Fig. 11, and the Subtraction of the deformed image from the reference image produced the resultant image pattern, shown in Fig. 12.

Data collected through laser speckle shearography is processed to yield quantitative measurements of deformation and the advantages of high sensitivity for measuring displacements in the micrometre range and a non-contact nature that preserves the integrity of solar cells.

## 4 Conclusion

Moiré pattern analysis, when combined with shock-induced vibration testing, serves as a powerful diagnostic tool for detecting busbar faults in solar cells. This method enables the early identification of stress accumulation, preventing mechanical failures and improving solar panel durability. The shearography method is used to detect the oversized vibration-induced deformation. The ability to detect strain, displacement, and deformation in real time makes it an ideal solution for photovoltaic system monitoring and fault prevention.

## References

- 1 Post D, Han B & Ifju P, *High Sensitivity Moiré: Experimental Analysis for Mechanics and Materials*, Springer (1994).
- 2 Chiang F P, *Opt Eng*, 27 (5) (1988) 275381.
- 3 Rastogi P K, *Photomechanics*, Springer-Verlag, (1994)
- 4 Sciammarella C A, *Exp Tech*, 25 (2) (2001) 11.
- 5 Cloud G, *Opt Methods Eng Analysis*, Cambridge University Press, (1995)
- 6 Sutton M A, Orteu J J & Schreier H W, *Image Correlation for Shape, Motion and Deformation Measurements*, Springer (2009).
- 7 Yamaguchi I, *J Appl Phys*, 55 (7) (1984) 1950.
- 8 Peters W H & Ranson W F, *Opt Eng*, 21 (3) (1982) 213427.
- 9 Moore D F, *Surface Analysis Methods Mater Sci*, Springer, (2001).
- 10 Maierhofer C, Reinhardt H W & Dobmann G, *Non-Destructive Evaluation of Reinforced Concrete Structures*. Woodhead Publishing, (2010).
- 11 Liu W, Li H & Lu J, *Sol Energy*, 120 (2015) 256.
- 12 Xie H, Wang Y & Liao W, *Meas Sci Technol*, 19 (11) (2008) 115701.
- 13 Grediac M, & Hild F, *Full-Field Measurements Identification Solid Mechanics*, Wiley, (2011)
- 14 Wang Z & Zhou X, *Sol Energy Mater Sol Cells*, 101 (2012) 45.
- 15 Jiang W, *et al*, *Int J Photoenergy*, 2016 (2016) 7890123.
- 16 Rao G R & Venkatraman B, *J Renew Energy Res*, 5 (4) (2015) 925.
- 17 Al-Jumaili S, *et al.*, *Renew Energy*, 123 (2018) 649.
- 18 Zhang T & Guo Y, *Sensors*, 20 (6) (2020) 1766.
- 19 Kang J, *et al.*, *IEEE Photovoltaic Specialists Confer*, (2017) 567.
- 20 Tiwari A & Agrawal R, *J Sol Energy Eng*, 140 (6) (2018) 061005.
- 21 Li J & Wang S, *Measurement*, 134 (2019) 518.
- 22 Nair S R & Thomas J, *Optik*, 228 (2021) 166166.
- 23 Singh P & Kumar R, *Sol Energy*, 206 (2020) 934.
- 24 Yadav R, *et al.*, *Energy Reports*, 6 (2020) 321.
- 25 Basu D K & Sundaram A, *J Opt Eng*, 53 (7) (2014) 071801.
- 26 Kumar A & Mehta V, *J Nondestruct Eval*, 38 (1) (2019) 1.
- 27 Verma A & Sharma R, *Renew Sustain Energy Rev*, 145 (2021) 111127.
- 28 Zhao Y & Lin X, *Appl Opt*, 59 (16) (2020) 4907.
- 29 Patel N, *et al.*, *Opt Laser Technol*, 153 (2022) 108277.
- 30 Joshi A & Bhardwaj R, *Opt Lasers Eng*, 119 (2019) 20.
- 31 Prakash M & Subramanian K, *J Photonics Energy*, 13 (2) (2023) 025501.