DEVELOPMENT A MECHANICAL SYSTEM FOR DIGITAL IMAGE CORRELATION IN MICRO TENSILE-COMPRESSION TESTING

PHÁT TRIỂN HỆ THỐNG CƠ KHÍ CHO PHƯƠNG PHÁP TƯƠNG QUAN ẢNH SỐ TRONG THÍ NGHIỆM KÉO-NÉN VI MÔ

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(Received: January 06, 2025; Revised: March 09, 2025; Accepted: March 12, 2025)

DOI: 10.31130/ud-jst.2025.011E

Abstract - Digital Image Correlation (DIC) is a crucial Non-Destructive Testing (NDT) technique widely applied in various industrial fields due to its flexibility and high accuracy. However, the performance of DIC in micro tensile-compression testing systems is often constrained by the stability and adjustability of mechanical components, particularly camera mounting systems. This study presents a specialized mechanical structure incorporating locking mechanisms, rotational axes, and sliding components, enabling precise and flexible adjustments of the camera's position and orientation. Vibration resistance was prioritized to maintain stability during testing. Experimental results demonstrated notable advancements in positioning accuracy, operational flexibility, and vibration resistance compared to conventional systems. This design offers an effective solution for laboratory and industrial applications, contributing to advancements in non-destructive material testing technologies.

Key words - Digital Image Correlation (DIC); Non-destructive testing (NDT); mechanical structure for DIC; system stability for DIC; Micro- tensile testing.

Tóm tắt - Phương pháp tương quan ảnh số (DIC) là một kỹ thuật kiểm tra không phá hủy (NDT) quan trọng, được ứng dụng rộng rãi trong công nghiệp nhờ tính linh hoạt và độ chính xác cao. Tuy nhiên, hiệu suất của DIC trong các hệ thống thử nghiệm kéo-nén vi mô thường bị giới hạn bởi độ ổn định và khả năng điều chỉnh của các thành phần cơ khí, đặc biệt là hệ thống gắn camera. Nghiên cứu này giới thiệu một hệ thống cơ khí chuyên dụng gồm cơ chế khóa, trục xoay và bộ phận trượt, cho phép điều chỉnh vị trí và góc của camera một cách chính xác và linh hoạt. Khả năng chống rung được ưu tiên để duy trì độ ổn định trong kiểm tra. Kết quả thử nghiệm thực tế cho thấy, hệ thống cải thiện đáng kể độ chính xác định vị, tính linh hoạt và khả năng chống rung, vượt trội so với các hệ thống thông thường. Thiết kế này cung cấp giải pháp hiệu quả cho các ứng dụng trong phòng thí nghiệm và công nghiệp, đồng thời thúc đẩy công nghệ kiểm tra không phá hủy vật liệu.

Từ khóa – Phương pháp tương quan ảnh số (DIC); phương pháp kiểm tra không phá huỷ (NDT); hệ thống cơ khí trong DIC; hệ thống ổn định trong DIC; thí nghiệm kéo nén.

1. Introduction

With the continuous advancement of the material industry, testing methods for materials are undergoing constant refinement to ensure their essential role in assessing product quality and safety. Destructive testing methods, such as tensile, compression, and impact testing, have notable drawbacks, including the irreversible damage they cause to test samples, high costs, and unsuitability for finished products. In contrast, Non-Destructive Testing (NDT) techniques enable the inspection of products without inflicting damage or altering their structural integrity. Currently, NDT methods such as ultrasonic testing, X-ray testing, and magnetic particle testing are widely used due to their effectiveness and non-invasive nature [1-3]. Among these, Digital Image Correlation (DIC) has emerged as a cutting-edge technique, offering unique advantages in material testing through its non-contact approach.

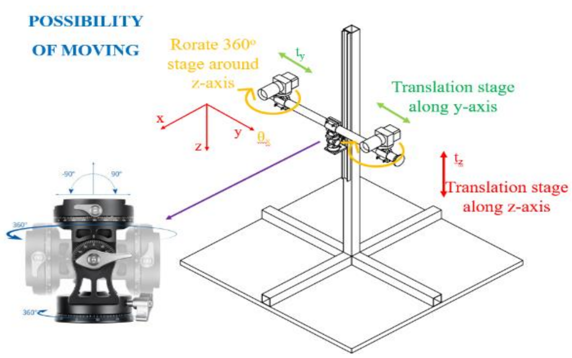
DIC is a versatile tool applicable to a wide range of materials, including metals, composites, and polymers, under diverse testing conditions [4–8]. It has found applications across industries such as aerospace, automotive, civil engineering, and material sciences. Additionally, the integration of DIC with in-situ tensile testing has been developed for full-field strain measurement at micro and nano scales [9-12]. This combination is widely utilized for generating strain distribution maps [13-17], assessing strain near crack tips [14, 18, 19], and determining material properties such as Young’s modulus, yield stress, Poisson's ratio, and stress intensity factors [20-23]. DIC enables capturing dynamic events like impacts or slow deformations under static loads, making it an indispensable technique for laboratory research and industrial product inspections. Its utility is particularly significant in industries like aerospace, automotive manufacturing, and construction, where consistent and reliable non-destructive testing is paramount. However, the precision of DIC measurements is heavily reliant on the stability and accuracy of the system's mechanical components, especially the camera mounting configurations. Despite its growing popularity, research on optimizing these mechanical structures for enhanced flexibility and stability remains limited.

This study aims to address these challenges by designing and manufacturing a specialized mechanical assembly to enhance the performance of DIC systems. The proposed system incorporates advanced locking mechanisms, rotational axes, and sliding components to enable precise and flexible adjustments of the camera's position and orientation. This ensures comprehensive and accurate surface observations during testing. Experimental evaluations validate the assembly's improved performance in terms of positioning accuracy, operational flexibility, and vibration resistance, thereby demonstrating its potential to enhance the reliability and application range of DIC systems in both laboratory and industrial settings.

2. System configuration

2.1. Mechanical design

The mechanical system of the DIC setup consists of several key components, as illustrated in Figure 1, each playing a crucial role in ensuring precise and reliable measurements during material testing. The primary structure includes a robust base and support column, providing stability to the entire assembly. The camera mounting systems, securely attached to the support, allows precise movement along both the Y-axis (horizontal) and Z-axis (vertical). A sliding mechanism, consisting of a carriage and guide rail, ensures smooth and controlled camera motion. Additionally, pan and tilt heads offer rotational capabilities, enabling optimal camera positioning through tilting and rotation. Together, these components function synergistically, allowing for flexible adjustments to accommodate various experimental configurations, particularly in large-scale material testing. The system is designed to support substantial loads while maintaining high precision, thereby ensuring reliable outcomes in DIC experiments.



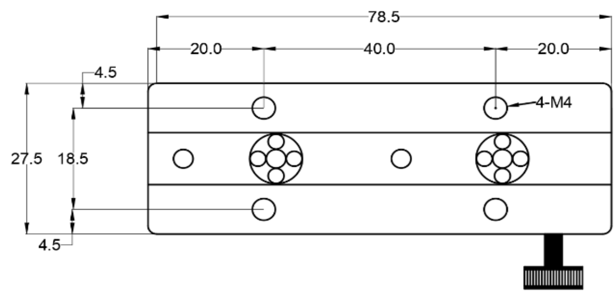
(a)

(b)

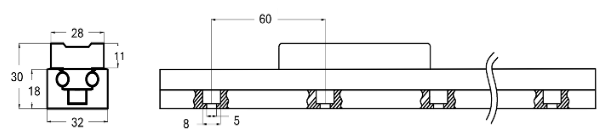
Figure 1. *Schematic of designed system (a) and 3D drawing of system (b)*

The base and primary support structure of the DIC system is constructed from stainless steel (Inox 201), chosen for its superior strength, durability, and corrosion resistance. This material ensures stability and robustness throughout experimental procedures. In addition, the frame is fabricated from square-section stainless steel with dimensions of 30×30 mm, using TIG welding techniques to achieve high precision and minimize alignment deviations. Moreover, the design is optimized to support substantial loads, ensuring reliability under various testing conditions. The base measures 1030 mm × 1030 mm, providing a solid foundation, while the overall height of 1100 mm allows flexibility across a diverse range of experimental setups and making it compatible with standard tensile testing machines. Finally, the use of stainless-steel balances weight and performance, further enhancing the system's stability.

The sliding mechanism includes an SGR10 guide rail and SGB10 linear bearing block, enabling smooth vertical camera movement along the Z-axis (100 mm to 1100 mm). Linear ball bearings are used to minimize friction and enhance precision. Guide rails and bearing blocks are assembled with an alignment tolerance of less than 0.05 mm.



(a)



(b)

Figure 2. *Parameter of SGB 10 carriage (a) and SGR 10 guide rail (b)*

The camera's horizontal movement along the Y-axis extends over a range of 400 mm in either direction, allowing wide-area coverage without repositioning the entire system. This motion is facilitated by the Q08S slider, which has a maximum length of 1000 mm, providing substantial horizontal travel. The pan and tilt heads play a crucial role in adjusting the camera's orientation. The panhead enables 360-degree rotation, allowing the camera precisely positioned around the specimen. This is particularly vital in 3D DIC setups where images from multiple perspectives are essential for generating a comprehensive 3D model of the specimen's deformation. Additionally, the tilt head enhances versatility by offering tilting capabilities up to 180 degrees, enabling the camera to capture images from above or below the specimen as required.

2.2. Imaging system

In a DIC system, selecting an appropriate camera is crucial for accurate and reliable measurements, as camera specifications directly impact image data quality.

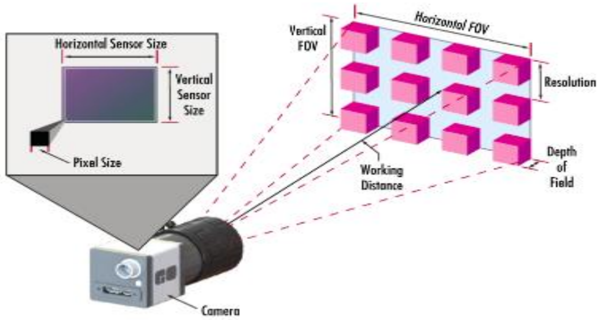


Figure 3. *Parameters of Camera and Lens*

For this DIC setup, the study employs the Blackfly S camera from FLIR, which meets the specific requirements for accurate and reliable image capture. This camera features a 2/3-inch CMOS sensor with a resolution of 2,448 x 2,048 pixels (5 Megapixels), providing high image clarity and detailed analysis. Its maximum frame rate of 22 fps enables capturing rapid movements, which is essential for real-time experiments involving dynamic deformation. The camera's shutter speed ranges from 11 µs to 30 seconds, offering versatility for various testing conditions from high-speed deformations to long exposure requirements. Additionally, it includes a C-mount for easy lens attachment and utilizes GigE (Gigabit Ethernet) technology for fast and reliable data transmission, minimizing latency in high-resolution imaging. These features make the Blackfly S a robust choice for achieving precise and efficient image capture in DIC applications.

When selecting a lens for a DIC system, several important specifications must be considered. Focal length (FL) determines the magnification and angle of view; a shorter focal length provides a wider field of view, while a longer one brings the subject closer. Field of View (FOV) refers to the visible area captured by the camera, which directly affects how much of the test sample is observed. Depth of Field (DOF) is the range within which objects stay in focus, crucial for capturing movements or deformations. A large DOF is preferred to ensure consistent focus. Aperture controls the amount of light entering the lens, with a higher f-stop providing a larger DOF. Lastly, working distance (WD), or the distance between the lens and the object, must accommodate the experimental setup to ensure flexibility and accurate imaging.

Using the known relationship between sensor size (width or height) and FOV, we can calculate the extent of the FOV for a specific lens setup.

$$Tan\left(\frac{AFOV}{2}\right) = \frac{HFOV}{WD} = \frac{\text{hh}}{f}$$

Or if we use the vertical size, it will be:

$$Tan\left(\frac{AFOV}{2}\right) = \frac{VFOV}{WD} = \frac{hv}{f}$$

Here, $AFOV$ denotes the Angle Field of View, $HFOV$ and $VFOV$ represent the horizontal and vertical fields of view, respectively, and WD stands for working distance.

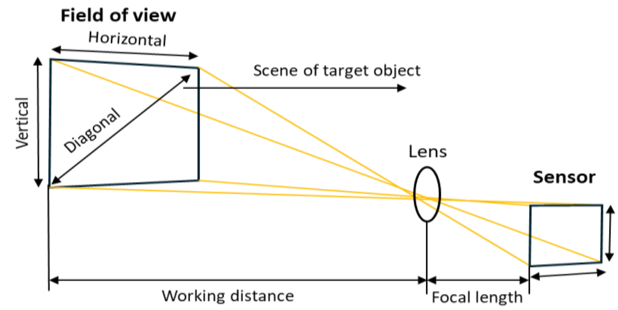


Figure 4. *Relationship between sensor size and field of view*

In the DIC system, the optimal FOV is 20x13.3 mm, scaled based on the camera sensor ratio. To minimize lens distortion, a telephoto lens with a focal length greater than 60mm is ideal. However, lenses with very long focal lengths are often too expensive and unnecessary for this application. Additionally, a small Angle Field of View (AFOV) is preferred. The camera's sensor size is 8.8x6.6 mm, and the lens aperture should range between f/5.6 and f/11. The working distance should be flexible to accommodate different systems, not just the tensile test. In this experiment, a 12.5-75mm FL 6X Lens has been selected to meet the specific requirements of the DIC setup. This macro lens features an adjustable focal length from 12.5mm to 75mm, providing the versatility needed to achieve a precise Field of View (FOV) of 20x13.3 mm. With an aperture range of f/1.2 to f/16, it allows flexibility in various lighting conditions while supporting an appropriate Depth of Field (DOF) for capturing clear images of the test specimen. The lens also has a working distance (WD) of over 1000mm, which accommodates different setups and maintains the required distance for clear, undistorted imaging. Its 6X zoom ratio allows for fine-tuning of magnification, essential for accurate displacement and strain measurements in DIC. This lens was chosen for its optimal balance between performance and cost-effectiveness, fulfilling all technical specifications necessary for reliable and precise DIC analysis.

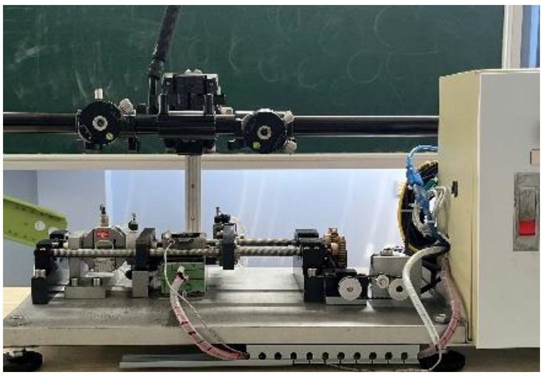
Illumination is critical in DIC experiments, affecting image clarity and contrast for accurate analysis. Consistent, uniform lighting minimizes contrast variations, reducing data interpretation errors. LED lighting is preferred for its diffuse illumination, preventing glare and specimen heating that can induce thermal expansion, thus improving measurement accuracy. Adjustable, flicker-free LED lights ensure stable contrast across the field of view. While room lighting may suffice for static or low-speed tests, controlled LED lighting is optimal for consistency across DIC setups. Furthermore, the quality of DIC measurements is critically influenced by the image contrast, which is enhanced through the application of a speckle pattern. Speckles should be spatially random and appropriately sized to ensure optimal performance of the DIC tracking algorithm. At the small macroscopic length scales considered in this study, the specimen naturally exhibits an isotropic surface texture with sufficient density, facilitating accurate subset matching.

Figure 5. *Speckled specimen*

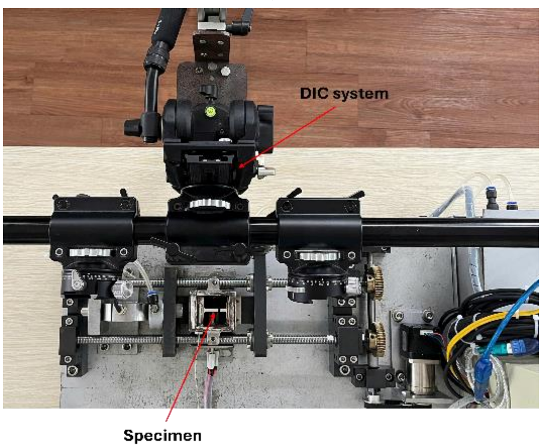
3. Results and Discussion

3.1. DIC system

Figure 6 shows the complete DIC system. This is the initial mechanical system that optimizes the setup process and improves accuracy in sample collection.



a)



b)

Figure 6. *The actual DIC system after finishing fabrication in front-view (a) and top-view (b)*

The system is adaptable to both vertical and horizontal tensile and compression testing machines due to the flexibility of panhead. Additionally, it can utilize a panel head in combination with a horizontal bar for 2D imaging. For more convenience, the Q08S bar can be eliminated if the test is only carried out in 2D case. In this case, the panel head can be installed directly on the panhead, making the setup much easier. To evaluate the accuracy of the system, the camera was programmed to move to a series of predefined positions along the designated axis. At each position, a laser displacement sensor was used to measure the actual displacement of the camera and compare it with the intended target position. The difference between these values was recorded as the positioning error. The experiment was repeated multiple times to ensure consistency. The results confirmed that the system meets the required precision standards.

3.2. Experimental evaluation of system performance

For DIC testing, a miniature machine was designed to carry out experiments on small size specimens with a suited loading capacity and over a wide range of crosshead speeds. Stress-strain curves obtained from tensile tests are fundamental for investigating a material's mechanical properties. To facilitate such studies, the authors have recently developed a novel miniature testing device. This micro-testing machine is specifically designed to perform experiments on small specimens, accommodating appropriate loading capacities and offering a broad range of crosshead speeds. Indeed, the device operates by pulling one end of the specimen while the other remains attached to a load cell that monitors the applied force. A stepper motor, capable of 200 steps per full rotation, drives the movable crosshead. For enhanced displacement precision, a high-resolution micro-stepping driver is utilized, allowing micro-step adjustments as fine as 1/256 of a step. During testing, specimen elongation is measured using a Linear Variable Differential Transformer (LVDT) with a range of ±6mm, while a 2kN capacity tension/compression load cell records the applied force. Signal conditioners are integrated with both sensors to enhance input resolution and improve the signal-to-noise ratio. Sensor data are digitized via a 16-bit data acquisition board and transmitted to a computer. The system is complemented by a Graphical User Interface (GUI) developed in the LabView environment. This interface enables users to set test conditions (e.g., sampling frequency, displacement rate), monitor real-time measurements (e.g., force versus displacement), and save results for subsequent analysis (see Figure 6). Based on DIC method, the strain estimation is shown in Figure 7. The calculated Poisson's ratio and Young’s modulus for the specimen was determined to be 0.24 and 35787 MPa, respectively. Image analysis results indicate that measurement errors were reduced by **15%** compared to fixed-camera setups, allowing for more accurate strain data acquisition.

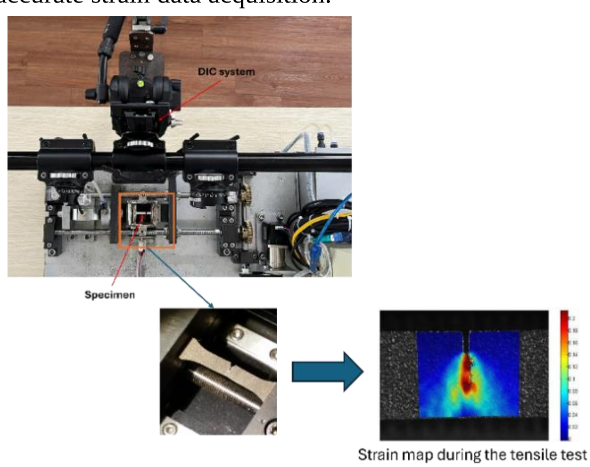


Figure 7. *Procedure applying DIC system for micro tensile testing process and results in a strain distribution map after analysing*

4. Conclusion

The development of a flexible mechanical system for DIC in micro tensile-compression testing has demonstrated significant advancements in system stability, precision, and adaptability. By incorporating specialized locking mechanisms, sliding components, and rotational axes, the proposed assembly enables precise and flexible camera positioning, ensuring comprehensive surface observations and improved vibration resistance during testing. Experimental results validate the system's ability to enhance positioning accuracy and operational reliability, highlighting its suitability for both laboratory and industrial applications. This study emphasizes the importance of optimizing mechanical structures to improve the performance of DIC systems, particularly in non-destructive material testing. The proposed design not only enhances the reliability and versatility of DIC applications but also provides a cost-effective solution for advancing material testing technologies. With the promising performance of the current system, future work will focus on testing additional tensile tests for welded joints and sintered joint specimens used in mechatronic packaging. Furthermore, the DIC system will be enhanced with an infrared camera to capture temperature propagation, enabling non-destructive evaluation and structural health monitoring applications.

Acknowledgment: This work was supported by The University of Danang - University of Science and Technology, code number of Project: T2023-02-04MSF.

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