INTERNATIONAL
DIGITAL IMAGE CORRELATION
SOCIETY

A Good Practices Guide for Digital Image Correlation

Standardization Committee

Month, YYYY

DRAFT – FOR REVIEW OF EDITION 2

Safety Disclaimer

This guide does not address the health or safety concerns regarding applying DIC in a mechanical testing or laboratory environment. It is the responsibility of the laboratory and user to determine the appropriate safety and health requirements.

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About this Guide

The International Digital Image Correlation Society (iDICs) was founded in 2015 as a nonprofit scientific and educational organization committed to training and educating users of digital image correlation (DIC) systems. iDICs is composed of members from academia, government, and industry, and develops world-recognized DIC training and certifications to improve industry practice of DIC for general applications, with emphasis on both research and establishing standards for DIC measurement techniques. More information can be found at www.idics.org.

To support this mission, the iDICs Standardization Committee was formed in part to develop guidelines for DIC practitioners. Details of the entire development and review process can be obtained through iDICs (info@idics.org), but they are summarized here. The working group on Good Practices, Reporting Requirements and Terminology (a subset of the committee) developed this Good Practices Guide for DIC. The working group was composed of expert DIC practitioners (see below), including representatives from many commercial DIC software packages, with diverse experience using DIC in a myriad of applications.

After a final draft of the guide was completed by the working group, a public comment period was opened in November 2017 through January 2018, during which any DIC practitioner could opt-in to review the Guide. In total, 100 people opted-in to the review process, 56 of whom returned official votes. Of the 56 received votes, 23 people voted “Approve without comment”, 32 people voted “Approve with comments and suggested revisions”, and 1 person voted “Disapprove with comments (at least one technical) and suggested revisions”. Over 500 comments were received (over 130 of which were technical comments), and the working group addressed each, either through revising the Guide, or through a written rebuttal. After that revision, the final version of the Guide and the working group responses to the comments were reviewed and approved by some of the members of the iDICs Executive Board, who did not participate in either the working group or the public comment period. Edition 1 of the Guide was officially released in October 2018.

During the public comment period for Edition 1 of the Guide, the Standardization Committee surveyed reviewers for what areas of the Guide needed to be prioritized for future improvement and expansion. Based on these results, the Global DIC working group and the Figure-Examples-References working groups were formed. Additionally, the Standardization Committee continued to collect editorial and technical comments about the entire Guide. Edition 2 of the Guide incorporates these additions and revisions. Similar to Edition 1, a draft of Edition 2 was first reviewed by the Standardization Committee, and then opened for public comment in MM-YYYY. [More information to be included about the voting process after it is complete.]

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Conventions

In this guide, certain items are highlighted, set aside, or labeled separately from the main body based on the following conventions.

Recommendation

"Recommendations" are suggestions about specific actions a DIC practitioner should take, or specific decisions a DIC practitioner should make. These suggestions are based on the collective experience and expertise of the working group members. Recommendations are intended to be ideal suggestions; in other words, for ideal DIC measurements within the scope of this document, a DIC practitioner would follow all recommendations.

Tip

"Tips" provide supplementary information that can be useful to a DIC practitioner, helping to design and execute DIC measurements. "Tips" are typically background information, targeted to either inexperienced DIC practitioners, or to experienced DIC practitioners working with advanced setups. "Tips" are differentiated from "Recommendations" in that "Tips" do not imply a specific action or decision that a DIC practitioner should follow.

Caution

"Cautions" provide information about events, decisions, or features that could have negative impacts on DIC measurements. "Cautions" are often followed by "Recommendations", which provide information on avoiding or mitigating the negative event, decision, or feature.

Example

"Examples" provide more detailed description of topics, using a particular example as an exemplar.

Local-Global Flag

"Local-Global Flags" indicate that a section or statement contains local DIC-specific information (such as mentions of subsets or step size), that should be dealt with carefully when using a global DIC method. Whenever a Local-Global Flag appears, the reader is referred to Appendix C for more details on global DIC specifics.

Footnote

Footnotes are reserved for supplementary information that is outside of the scope of this edition of the guide. Their primary purpose is to inform the reader when the guidelines given in this guide are not applicable, to ensure that the guidelines are applied appropriately. The remarks made in footnotes are brief, because the pieces of information contained in the footnotes are outside of the scope of this edition of the guide.

Appendix

Appendices are reserved for supplementary information that, due to length or complexity, would clutter and defocus the main body of text.

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1 — Introduction

1.1 Aims and Basic Principles of DIC

Within the scope of this guide, DIC is an optically-based technique used to measure the evolving full-field 2D or 3D coordinates on the surface of a test piece throughout a mechanical test. The measured coordinate fields can be used to calculate derived field quantities-of-interest (QOIs), such as displacements, strains, strain rates, velocities, and curvatures. Because DIC is a non-contact technique that is independent of the material being tested or the length-scale of interest, it can be used in a wide variety of applications to investigate and characterize the deformation of solids. Some common materials that are tested include metals, polymers, concrete, geological samples, biological tissues, battery electrodes, explosives, etc. and test pieces range from, for example, small coupons used in tensile tests up to entire sub-assemblies of aircraft. This versatility has led to a plethora of methodologies and software codes, both commercial and independently developed, to utilize the data captured from a DIC measurement. For a list of DIC software packages, see the iDICs website at `https://idics.org/resources/`.

To begin, the basic concepts of DIC are introduced here. For a more complete introduction to DIC, one should consult [1]. For a practical guide to getting started with DIC, the reader is also directed to the series of articles in [2]. At the core level, DIC estimates full-field coordinates and displacements from a sequence of digital images taken of a pattern on the surface of a test piece, by solving an optimization problem, typically based on a transport model such as optical flow [1, Sec. 5.2], [3]. A fundamental assumption in DIC measurements is that the pattern on the surface of the test piece, either natural or applied, follows the deformation of the underlying test piece. Thus, the images of the test piece taken throughout the test can be correlated to produce full-field coordinates representative of the shape, motion and deformation of the surface of the test piece. 2D coordinates of the surface can be measured using a single camera system, and this is referred to as 2D-DIC. 3D coordinate measurements of the surface require a minimum of two cameras[1] oriented at a stereo-angle to perform 3D photogrammetry in addition to image correlation [1, Sec. 4.2], [4]; this is called stereo-DIC.[2] Fig. 1.1 shows a schematic of 2D- and stereo-DIC. Before measurements are made, the camera/lens system is calibrated by imaging features of known separation lengths (i.e. a calibration target). This calibration allows DIC software to correct for lens distortions and, for stereo-DIC, provides the location and orientation of the cameras in space with respect to each other, and to the test piece.

There are many types of software developed to perform this correlation, but the two most common categories are local and global DIC methods. In a local method, the coordinate solution at a point

[1] Stereo-DIC can be performed with a single camera using stereo optics, where the left and right halves of the detector are taken as the left and right images. This is an advanced topic, though, and beyond the scope of this edition of the guide.

[2] Stereo-DIC is often commonly called 3D-DIC. However, to avoid confusion with volumetric-DIC, this Guide recommends the term stereo-DIC instead of 3D-DIC. See the Glossary entry "Digital Image Correlation" for more information.

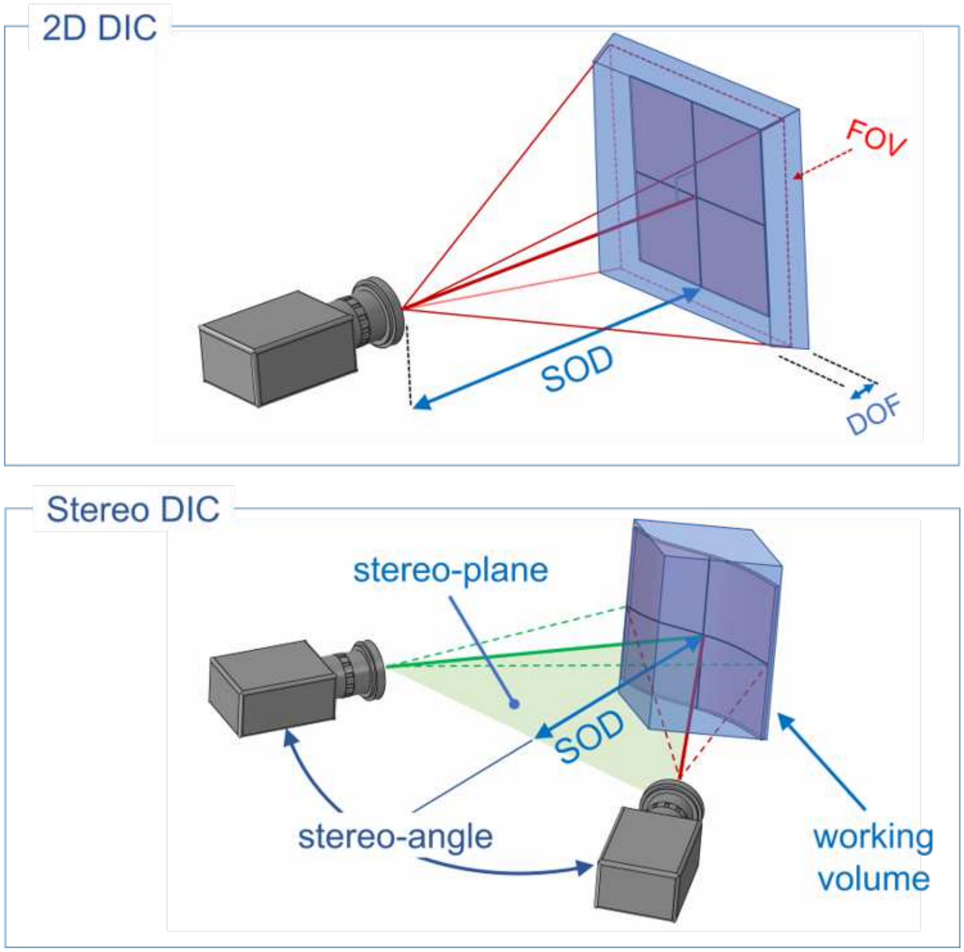


Figure 1.1: Schematic illustrating the differences between 2D-DIC and stereo-DIC. Stand-off distance (SOD), field-of-view (FOV), depth-of-field (DOF), stereo-angle, stereo-plane, and working-volume are also defined.

depends only on a small subset of the image in the vicinity of that point, but is otherwise independent of the solution at all other points of interest. In a global method, the solution at one point has some dependence on the solution at other points in the vicinity of the point of interest. For the most part, the content of this guide is applicable to both methods, especially concerning the Design of DIC Measurements (Ch. 2), Preparation for the Measurements (Ch. 3), and Execution of the Test with DIC Measurements (Ch. 4); however, this guide is written from the perspective of local DIC when discussing the Processing of DIC Images (Ch. 5). Therefore, Appendix C has been written with global DIC users in mind to separately address the specifics of global DIC. Moreover, "Local-Global Flags" throughout this guide denote sections or statements that contain information specific to local DIC and refer the reader to Appendix C for information specific to global DIC.

In brief, a software code analyzes a user-defined region-of-interest (ROI) within the images, which contains a set of interrogation points, also called measurement points or data points. In local DIC, each interrogation point is centered within a subset of the image. The interrogation points are typically defined at some regular spacing (step size), such that neighboring subsets may (or may not) overlap.

The subsets are numerically correlated from the reference image (before motion/deformation) to each subsequent image (during motion/deformation). See Fig. 1.2 for an illustration of some of these terminology definitions. This correlation is performed by first approximating the pattern in each subset using an interpolant function [1, Sec. 5.6.1 and Sec. 10.2.3.2], [5, 6], and then allowing that function to deform from the reference image based on a subset shape function [1, Sec. 5.3], [6, 7]. A matching criterion [1, Sec. 5.4], [8–10] in conjunction with subset weights is used to match each subset in the reference image with the corresponding subset in the deformed images. In stereo-DIC, the matching criterion, along with the parameters of the stereo-system calibration, are used to match subsets from one of the cameras to the other camera. The result of the correlation is the measured coordinates of the center of each subset. A corresponding algorithm exists for global DIC (see Appendix C.1).

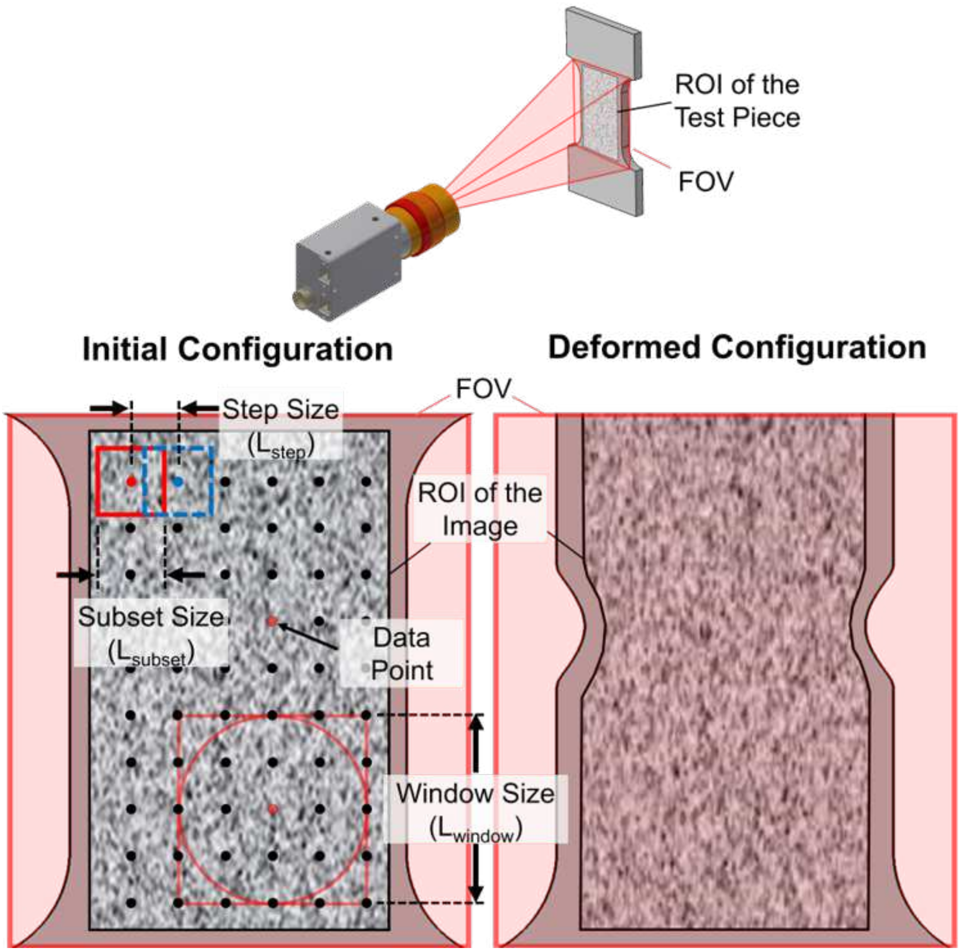


Figure 1.2: Schematic illustrating several terminology definitions, including the ROI of the test piece, subset and subset size, step size, window size (representing, for example, a strain window or a filter window) , field-of-view (FOV), and data point (also called interrogation or measurement point).

The calculation of derived field quantities is the final step in many DIC processing schemes. The most commonly derived quantities from these coordinate fields are probably strains, though DIC provides access to other QOIs, such as curvature, velocity, and acceleration. The minimum resolution (also called the noise-floor) of the QOIs, as well as potential bias errors, are tied to both the measurement setup (e.g. camera selection, image contrast, DIC pattern feature size), and the data processing parameters (e.g. subset size, subset shape function, virtual strain gauge for local DIC; and element shape function and element size for global DIC). Therefore, determination of the resolution of the QOIs through quantification of the measurement uncertainty completes the DIC data processing. This leaves the user with a full-field description of displacements, and/or derived quantities, of a test piece subjected to a mechanical test, as well as the uncertainties of those measurements.

1.2 Scope of this Guide

The purpose of this document is to provide good-practice guidelines for conducting DIC measurements in conjunction with mechanical testing of a planar test piece. This guide is designed to be both a primer training document geared towards new practitioners of DIC (supplementing vendor-based or other formal training and hardware- and software-specific documentation), as well as a reference for experienced users, to refresh their fundamentals knowledge and skill sets and assist them in troubleshooting DIC measurements. Appendix A provides a checklist of the major points to consider when designing, executing, and analyzing DIC measurements, while Fig. A.1 illustrates the steps of a typical mechanical test with DIC measurements in graphical form. Details for each step of the checklist and the flow chart are presented in the body of each section of this guide. The goal of this guide is to aid DIC practitioners in achieving well planned, well executed, well analyzed, and well documented DIC measurements. Note that this guide does *not* provide any guidelines for the mechanical test itself; it focuses only on the complementary DIC measurements.

In developing this guide, we strove to include as many instructive and diagnostic suggestions as possible, while still keeping the document general, and independent of specific hardware or software packages. As this document is a guide and not a standard, the guidelines presented here are not strict requirements for DIC measurements, but rather are suggestions for good practices. However, some guidelines are considered to be crucial for reliable and trustworthy measurements, while others are recommendations that serve to increase confidence in the measurements. This guide attempts to delineate between crucial and recommended guidelines, and provide cautionary notes about the consequences of omitting each guideline.

This guide focuses on good practices for DIC measurement setup, image correlation, and basic post-processing of DIC data for strain computations. It does not cover other data processing, such as velocity, acceleration, curvature, etc., nor specific data analysis applications that utilize DIC data, such as Finite Element Model (FEM) validation, material identification, etc.

The scope of this edition of the good practices guide is limited to common laboratory test conditions, as outlined in Sec. 1.3. Our intention is to incorporate good practices for complex test conditions, and their associated additional challenges, in a future edition of this guide.

1.3 Scope for Common Mechanical Tests with DIC Measurements

This guide applies to the following conditions found in typical mechanical test arrangements and associated DIC setups:

- Test piece size of approximately 50 mm to 1 m

- Planar test pieces undergoing nominally planar motion and/or deformation
- Strain range of up to approximately 60% equivalent strain
- General purpose laboratory testing with a well-controlled environment (e.g. room temperature of 15–25°C, and minimal vibrations)
- No special environmental conditions (e.g. no environmental chambers, no water tanks or pressurized vessels, no windows or viewports, no explosions or shock waves)
- Optical-based images (no images based on, for example, scanning electron microscopes, atomic force microscopes, or X-rays)
- 2D-DIC and stereo-DIC[3]
- Single DIC system: One camera for 2D-DIC and two cameras[4] for stereo-DIC[5]
- Standard machine vision cameras and optical lenses (no images from, for example, microscopes, stereo microscopes, or high-speed cameras)
- Local, subset-based DIC algorithms in the main text, as well as global DIC algorithms in Appendix C

The speed of the mechanical test, i.e. quasi-static versus dynamic, is not specifically scoped in this guide, as none of the guidelines presented here are limited to a certain range of grip velocities or strain rates.[6]

[3] Volumetric DIC (DVC) and other image processing techniques such as image stitching, photogrammetry data alignment, point tracking, object tracking, etc. are not discussed.

[4] See footnote 1 on page 1.

[5] The use of multiple cameras or multiple systems covering different regions-of-interest of a test piece, e.g. around a cylinder, is not discussed.

[6] There are some caveats to the applicability of this guide to dynamic tests. First, this guide is limited to standard machine vision cameras and excludes high-speed cameras, due to additional hardware complexity. High-speed cameras are defined here as cameras that record data in a burst to a RAM buffer on local camera memory that must be downloaded afterward. Second, special care and attention is often required when selecting a DIC pattern for dynamic tests, and this guide does not provide any guidelines, tips, or recommendations regarding this topic. Third, synchronization — both between cameras for stereo-DIC and between the camera(s) and other data of interest (e.g. force) — is often more complex for dynamic tests, but this guide only discusses the most basic need for camera synchronization for stereo-DIC. These and other features of dynamics tests are all beyond the scope of the current edition of this guide.

2 — Design of DIC Measurements

2.1 Measurement Requirements

Before conducting DIC measurements, clearly define the expectations and requirements of the mechanical test, and the objectives of the DIC measurements. The limits chosen here will be used later to assess if the analyzed results are within, approaching, or past the limits for which the DIC measurements were designed.

2.1.1 Quantity-of-Interest

Select the quantity-of-interest (QOI) such as shape, displacement, velocity, acceleration, strain, strain-rate, etc.

2.1.2 Region-of-Interest

Select the region-of-interest (ROI) of the test piece, and determine the expected motion and/or deformation of this region. The ROI may be a specific portion of the entire test piece (e.g. the gauge length and exposed end tabs of a uniaxial test piece). See Fig. 1.2 for a depiction of the ROI.

2.1.3 Field-of-View

Determine the required field-of-view (FOV) based on the ROI of the test piece and expected motion and/or deformation of the test piece. See Fig. 1.1 and Fig. 1.2 for a depiction of the FOV.

Recommendation 2.1 — ROI and FOV

Typically, the ROI of the test piece should almost fill the FOV to optimize the spatial resolution, while still remaining in the FOV throughout the test. For stereo-DIC, where the FOV is not the same in each camera, the effective FOV is the common FOV that is captured in both cameras, i.e. the portion of projected images to each camera of the same region of space. See Sec. 2.2.2 for more information about designing a camera mounting system to obtain the desired FOV.

2.1.4 Position Envelope for Hardware

Estimate the potential position envelope for cameras, mounting hardware, and lights to determine feasible stand-off distance (SOD) and location. See Fig. 1.1 for a depiction of the SOD. Determine what size and type of calibration target will be used (e.g. front-lit or back-lit) and how the mechanical test setup will need to be modified in order to calibrate the optical system (Sec. 3.2.2.2). Select (and purchase or fabricate if necessary) appropriate equipment for camera support structure (Sec. 2.2.2).

Tip 2.1 — FOV, lens focal length, and SOD

For more information on the relationship between the FOV, lens focal length, camera detector size, and SOD, see Appendix B.

Recommendation 2.2 — Backdrop

Consider adding a stationary backdrop behind the test piece, to prevent any people or objects moving behind the test piece from adversely affecting the images.

2.1.5 2D-DIC vs Stereo-DIC

Determine if 2D-DIC or stereo-DIC will be used. See Fig. 1.1 for an illustration of a 2D-DIC setup and a stereo-DIC setup.

Caution 2.1 — 2D Planar Assumption

For 2D-DIC, the test piece is assumed to be planar, to remain planar throughout the test, to be perpendicular to the camera optical axis,[a] and to maintain constant SOD throughout the test. Any inadvertent out-of-plane motion (i.e. due to test piece thinning or buckling, rotations or translations induced by misaligned grips, etc.) will cause errors in 2D-DIC [4, 11, 12].

Recommendation

Stereo-DIC is strongly recommended over 2D-DIC for all tests if possible, even tests in which a nominally planar test piece undergoes nominally planar deformation. 2D-DIC is recommended only if the geometry of the test setup cannot accommodate two cameras/lenses (i.e. when two cameras cannot physically fit into the position envelope available given the load frame and other equipment placement).[b,c]

[a] If the intrinsic and extrinsic parameters of a 2D, single camera system are calibrated using a calibration target as described in Sec. 3.2, then an out-of-plane tilt of the test piece can be determined and corrected. However, this is an advanced topic that is outside the scope of the current edition of this guide.

[b] Lack of availability of two cameras/lenses due to cost can also prevent the use of stereo-DIC. However, this typically only applies to high-speed or ultra-high-speed cameras, which are outside the scope of the current edition of this guide, and not to standard machine-vision cameras.

[c] 2D-DIC may also be required when testing highly porous foams, because the natural pattern created by the pores can appear differently in the left and right cameras (due to different perspectives, lighting, and shadows of each camera looking "into" the pores), and because applying a DIC pattern to the surface of the foam can be difficult. However, specific details about foam materials are beyond the scope of the current edition of this guide.

Recommendation 2.3 — 2D Out-of-Plane Errors

If 2D-DIC must be used, estimate the expected out-of-plane motion/deformation of the test piece during the test (due to test piece thinning, for example) and the corresponding error of in-plane measurements as described in Example 2.1 and Sec. 5.4.3.

Example 2.1 — Estimating 2D-DIC Strain Errors due to Out-of-Plane Motion

A key advantage of stereo-DIC over 2D-DIC is the ability to account for out-of-plane motion. In a 2D-DIC setup, only a single camera is used to capture the motion of a test piece. As a result, if the test piece moves out of plane, the DIC correlation will interpret that motion as a false strain on the surface of test piece. Some common examples of scenarios where false strain could occur include: imperfect alignment of the motion of a test piece with respect to the camera (i.e. the test piece is not or does not remain perfectly perpendicular to the camera), or thinning/ buckling of the test piece during deformation.

For example, a simple pin hole model is shown schematically in Fig. 2.1. If a test piece of height h moves rigidly out of plane an arbitrary distance (Δd) further away from the camera (without deformation), the test piece height remains constant. However, the camera will detect a change in magnification from m_1 to m_2 and a corresponding change in the angle α defined by the stand-off distance and the test piece height.

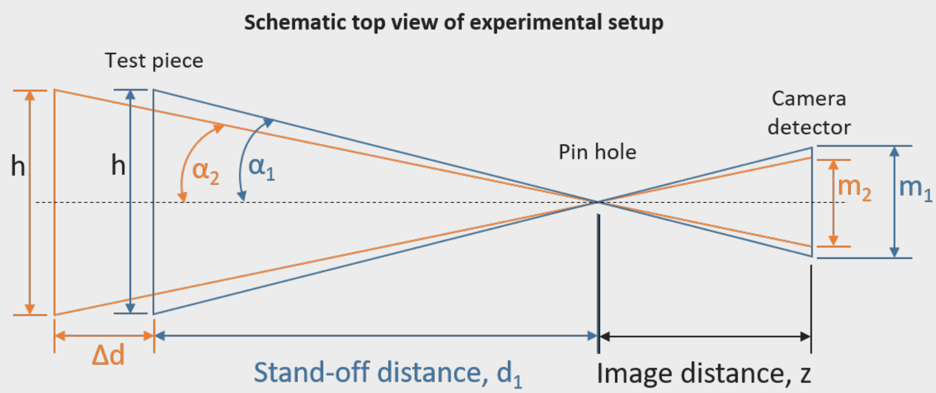


Figure 2.1: Schematic showing an experimental setup where a test piece of height h moves away from the camera a distance of Δd, which will lead to a change in magnification in the camera detector.

A simple estimate can be performed by using trigonometry to calculate the resultant change in magnification which is approximately the false strain likely to be reported in any DIC correlation (Eqns. 2.12.3–).

$$\tan(\alpha_1) = \frac{h/2}{d_1} = \frac{m_1/2}{z} \tag{2.1}$$

$$\tan(\alpha_2) = \frac{h/2}{d_1 + \Delta d} = \frac{m_2/2}{z} \tag{2.2}$$

$$\text{False Strain} \approx \frac{m_2 - m_1}{m_1} = \frac{d_1}{d_1 + \Delta d} - 1 \tag{2.3}$$

The magnitude of this false strain is dependent on the experimental setup, specifically the stand-off distance d_1, as can be seen in Eqn. 2.3. Table 2.1 shows that as the SOD increases, the false strain magnitude decreases. Thus, one possible method to reduce (limit) false strains in

2D-DIC is to select optics with longer focal lengths, which will require a longer SOD for a given constant FOV (see Sec. 2.2.1). It is always recommended to estimate the magnitude of false strain for a 2D-DIC setup and compare the values obtained with both your noise floor and the magnitude of a desired QOI.

Table 2.1: The effect of stand-off distance, d_1, on false strain magnitude

d_1	Δd	**False Strain**
250 mm	1 mm	0.4%
500 mm	1 mm	0.2%
1000 mm	1 mm	0.1%

2.1.6 Stereo-Angle

For stereo-DIC, select the required stereo-angle. See Fig. 1.1 for a depiction of the stereo-angle.

Tip 2.2 — Stereo-Angle

The stereo-angle depends on geometry of the test setup and the QOI that is most important. Smaller stereo-angles lead to better in-plane displacement accuracy, at the cost of increased out-of-plane uncertainty. Alternatively, larger stereo-angles lead to better out-of-plane displacement accuracy, at the cost of increased in-plane uncertainty.

This relationship between stereo-angle and uncertainty is also affected by the focal length of the lens. Shorter focal length lenses require a larger stereo-angle to obtain the same out-of-plane uncertainty as longer focal length lenses.

The stereo-angle also affects the useable DOF. With smaller stereo-angles, the test piece will remain in focus in both cameras over a larger range of out-of-plane motions. Conversely, with larger stereo-angles, the allowable out-of-plane motion to keep the test piece in focus is reduced.

Recommendation 2.4 — Stereo-Angle

Typically, the stereo-angle should be between approximately 15–35 degrees [13]. To reduce out-of-plane uncertainty and maximize useable DOF, short focal length lenses (8-12 mm) should have a minimum angle of 35 degrees and mid-range focal length lenses (17 mm) should have a minimum angle of 25 degrees; lenses with a focal length of 35 mm or longer can have a stereo-angle of 15 degrees [14].

Caution 2.2 — Large Stereo-Angles

Experience has shown that large stereo-angles (greater than approximately 35 degrees) may lead to difficulties in cross-correlation between the two cameras, due to large perspective differences in the images from each camera, especially with wide angle lenses.

2.1.7 Depth-of-Field

For stereo-DIC, determine the required depth-of-field (DOF) so that the entire ROI of the test piece remains in focus during the entire test, taking into account the expected out-of-plane motion, and the stereo-angle of the cameras. See Fig. 1.1 for a depiction of the DOF.

Tip 2.3 — Depth-of-Field

For 2D-DIC, the test piece is assumed to be planar and to remain planar with constant SOD. Therefore, DOF is not a large factor in the design of a 2D-DIC setup. However, having sufficient DOF helps ensure that the images will be in focus when the test piece is inserted into the load frame, and reduces sensitivity to alignment of the test piece and load frame with the optical axis of the imaging system. Additionally, having sufficient DOF will help ensure that focus will be maintained even during unexpected out-of-plane motion and/or deformation.

2.1.8 Spatial Gradients

Estimate the expected spatial gradients in the QOI. This will determine the required spatial resolution of the DIC system, which is a function of measurement design parameters such as image size and FOV, and DIC processing parameters such as subset size and step size for local DIC, and element shape function and element size for global DIC.

Tip 2.4 — Spatial Resolution

If the spatial gradients of the QOI are higher than the maximum gradients that the DIC system can resolve, consider increasing the magnification of the optical system (i.e. increasing the image scale) by (1) using a camera with larger image size or by (2) reducing the ROI of the test piece to be a smaller portion of the test piece.[a] These tips assume that the spatial resolution of the DIC system is camera limited, meaning that increasing the number of pixels across the ROI directly improves the spatial resolution of the DIC system. However, at high magnification (small FOVs) or large image size, the system may be lens-limited, meaning that further increase in magnification or image size will not improve the spatial resolution [15].

[a] Alternatively, two DIC systems could be set up, one at a lower magnification and with a larger FOV and larger DIC pattern features, to capture the overall motion and deformation of the test piece, and a second system at a higher magnification focused on a smaller ROI of the test piece with smaller DIC pattern features, to capture a localized region of sharp gradients. This advanced topic, however, is outside the scope of the current edition of this guide.

Example 2.2 — Camera Selection Based on Strain Gradients

In this example, the focus is determination of the image size required to accomplish a desired measurement. Knowledge of the expected displacement distribution, or strain distribution, is necessary for initial assessment of the DIC system to capture the QOI. This information may come from engineering experience, numerical analysis (e.g., finite element analysis), or theoretical knowledge (e.g., elastic solution). Here, we employ the latter approach.

The mechanical test under consideration is a long rectangular tensile specimen with a hole in the middle that is being elastically stretched in the x-direction (long direction), Fig. 2.2. The QOIs are the engineering strain along the x-axis, e_{xx}, and engineering strain along the y-axis, e_{yy}, from the edge of the hole to the edge of the specimen (blue lines in Fig. 2.2). It is assumed that having the measurement start one specimen thickness from the edge (dotted line in Fig. 2.2) is acceptable. However, it would be preferred to monitor the entire specimen length throughout the experiment (accomplishable using FOV 1 in Fig. 2.2), but if that is not possible, it would be acceptable to measure just the area close to the hole (see FOV 2 in Fig. 2.2). Only elastic strains are considered here, so the analysis will assume an applied stress of 90 % of the yield stress.

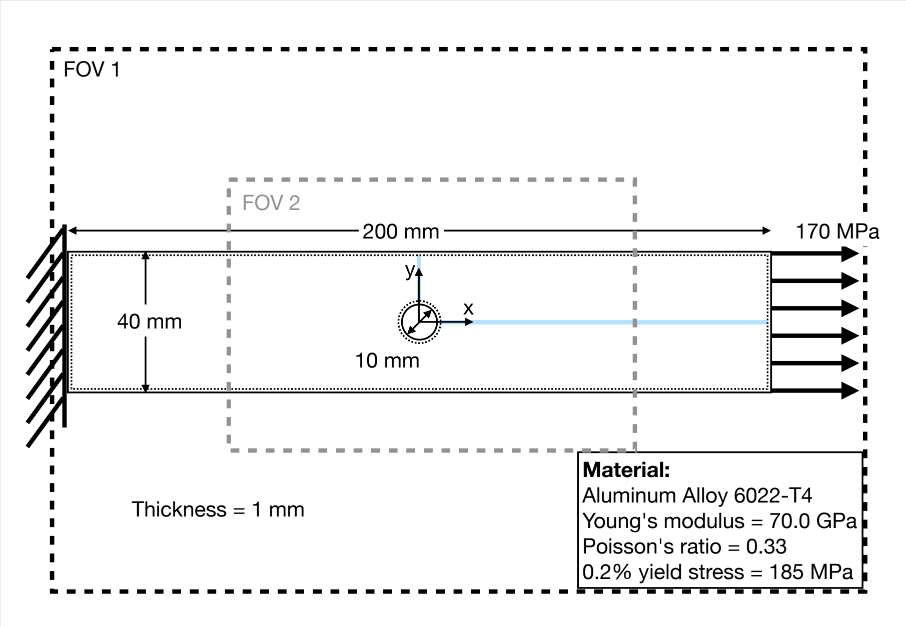


Figure 2.2: Schematic of test piece with two potential field-of-views (FOV1 and FOV2).

The camera detector resolutions being considered are 1.3 MP (1280 px × 1024 px), 5 MP (2448 px × 2048 px), and 20 MP (5472 px × 3648 px). Either field of view is achievable with these cameras given the proper lens selection, which is not shown here. For a nearly ideal pattern size, coverage, and contrast, a reasonable set of user-defined DIC analysis parameters are subset size of $L_{\text{subset}} = 31$ px (Sec. 5.2.6, Recommendation 5.2, and Tip 5.5), step size of $L_{\text{step}} = 11$ px (Sec. 5.2.7), and a Gaussian weighted strain filter window of size $L_{\text{window}} = 11$ data points.

For this example, a theoretical solution for this mechanical test assuming plane stress provides the "true" displacement and strain fields [16]. Two methods are compared to approximate the strain fields that would be obtained from DIC. Both of these methods could also be applied to a displacement or strain field extracted from a numerical analysis (e.g. FEA). The key to both methods is to estimate the DIC strains from the assumed "true" solution (e.g. theoretical or FEA), accounting for filtering effects from user-defined DIC analysis parameters such as subset size, subset shape function, step size, and strain or filter window.

The first method, Method 1, starts with the theoretical solution for the displacement fields. First, the image scale is calculated from the FOVs and image sizes stated earlier, and the displacements are computed at each pixel. Next, to approximate the effect of subset shape function attenuation bias of an affine subset shape function [1], the displacement results are averaged over the subset size. A moving average is used, so that the attenuated displacements are reported at each data point, separated by the step size, starting with a point one half subset from the hole edge. Then, the engineering strains are computed by calculating the local gradient in displacements at each point to its neighboring points divided by the point spacing (central difference approximation). Finally, the strain values are smoothed using a moving Gaussian weighted filter over all the strain points. This results in a VSG size of 144 px according to Eqn. 7.2, which equates to 26.0 mm, 13.6 mm, and 6.1 mm for the 1.3 MP, 5 MP, and 20 MP image sizes, respectively.

The second method, Method 2, starts with the theoretical solution for the strain fields, which again are calculated at each pixel location similar to the displacements used in Method 1. To approximate the attenuation bias of DIC, the theoretical strain values are simply smoothed with a moving Gaussian weighted filter over all pixel locations with a window size of the VSG length, L_{vsg}. Again, a moving window is used; however, since Method 2 does not assume a step size, the strains are reported at every pixel location that is at least as far from the edge of the test specimen as in Method 1. This method will capture the general trends of the data smoothing, but not the discrete nature of the DIC data due to the step size spacing, nor the smoothing due to different subset sizes and subset shape functions. The VSG size used was 141 px as before, but this is not associated with a single combination of subset size, step size, and filter window size (i.e. many combinations of subset size, step size, and filter window size could result in that VSG size).

Fig. 2.3a plots the results for e_{xx} along the x-axis and Fig. 2.3b plots e_{yy} along the y-axis, computed with Method 1 (solid lines with data points) and Method 2 (dot-dashed lines), with the theoretical strains shown as solid black lines. Results are only shown from the edge of the hole to x $\leq$ 15 mm and y $\leq$ 15 mm, since the region near the hole has the highest strain gradients and thus is the most challenging region to accurately capture. The strain error (bias) is calculated as the measured strain minus the theoretical strain value, and is plotted for e_{xx} and e_{yy} in Fig. 2.3c and d, respectively. As the image size is increased and VSG size (in terms of millimeters) is decreased, the DIC-estimated strain approaches the theoretical strain. That is, the peak strains near the hole are attenuated less, and the error is reduced. If none of the potential image sizes would meet the desired accuracy over the entire desired ROI for the test piece, then reducing the FOV (e.g. to FOV 2 in Fig. 2.2) might be considered, following Tip 2.4.

Therefore, the second FOV (FOV 2 in Fig. 2.2), that is half as wide, was similarly assessed for the same three image sizes. The results for the strain error with FOV 2 are presented in Fig. 2.4a and b, similar to Fig. 2.3c and d for FOV 1. By reducing the FOV to half the size, but keeping all DIC settings (in terms of pixels) the same (i.e. subset size of $L_{\text{subset}} = 31$ px, step size of $L_{\text{step}} = 11$ px, and strain filter window size of $L_{\text{window}} = 11$ data points), the VSG size (in terms of millimeters) is similarly reduced in half for each resolution (see legends in Fig. 2.3 and Fig. 2.4). With the smaller FOV and smaller VSG size (in terms of millimeters), the strain profile measured with DIC more closely matches the theoretical profile, with less attenuation of the peak strains in regions of high strain gradients. Additionally, since the subset size dictates the location of the first data point from the edge, and FOV 2 has a smaller subset size (in terms of mm) than FOV 1, the first data point from the hole edge is closer to the edge for FOV 2 than for FOV 1.

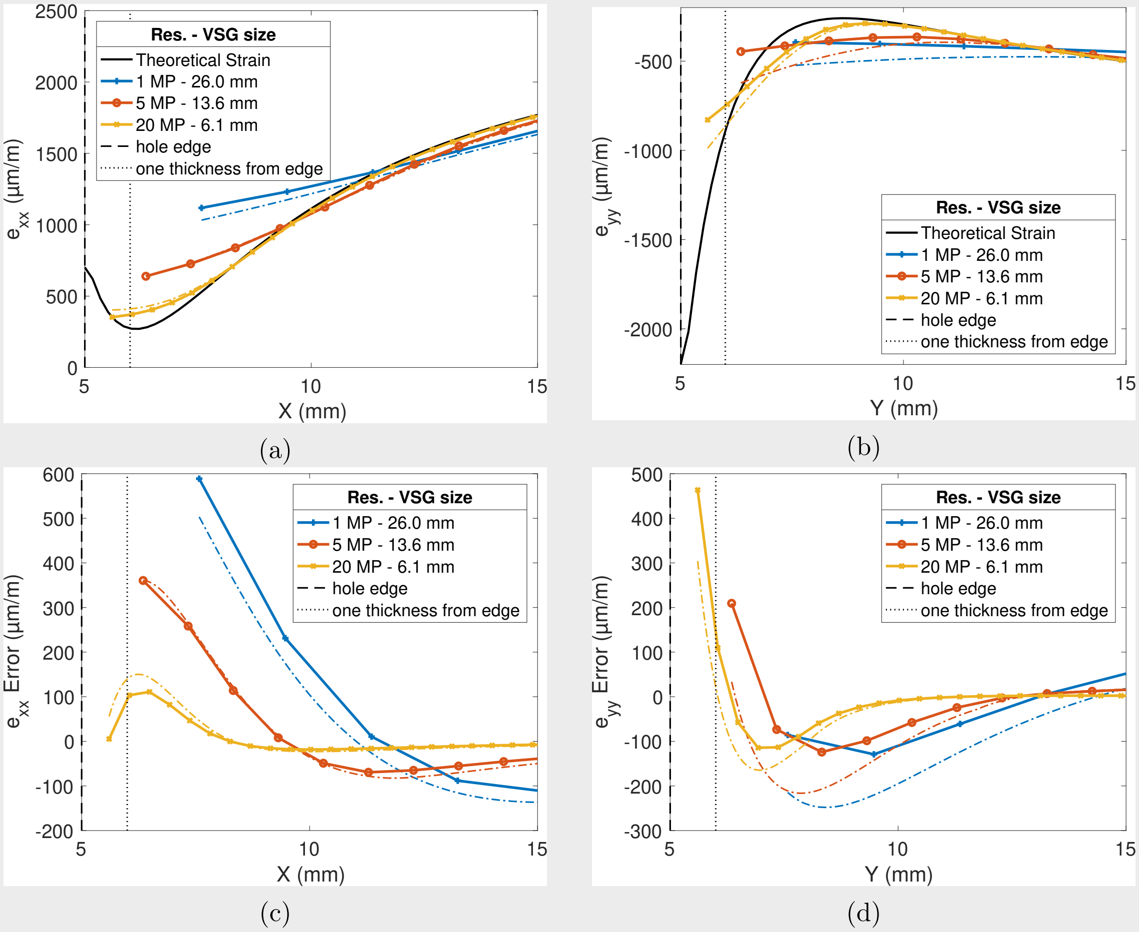
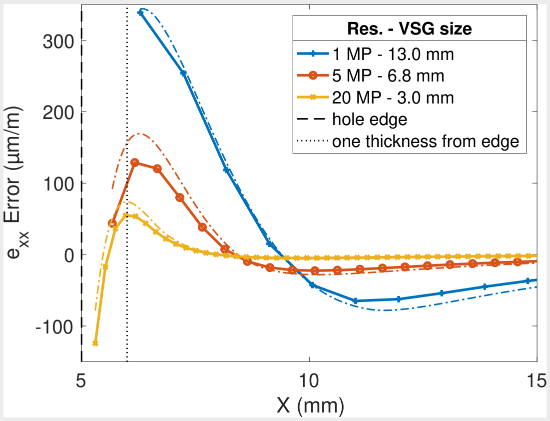
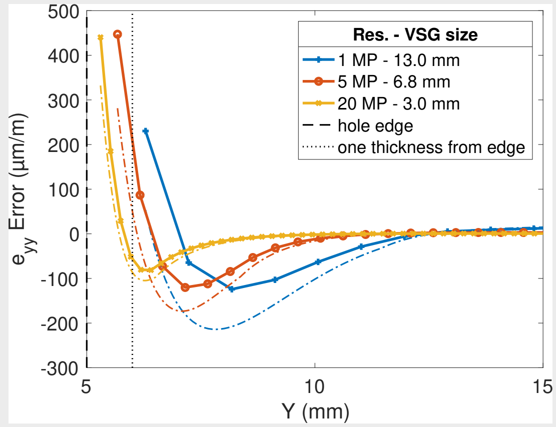


Figure 2.3: FOV 1 results for Method 1 (solid lines with symbols) and Method 2 (dot-dashed lines) with strain profiles (a) and (b) and strain error profiles (c) and (d) from hole edge to 15 mm along x- and y-axes, respectively. Solid black lines are the theoretical strain profiles.



(a)



(b)

Figure 2.4: FOV 2 results for strain error from the hole edge to 15 mm along each axis (a) along x-axis and (b) along y-axis, for Method 1 (solid lines with symbols) and Method 2 (dot-dashed lines).

Based on these results, a user could select the correct combination of camera (image size) and FOV for their intended measurement. For example, if the measurement needed to have a bias no greater than ± 150 µm/m starting one thickness from the edge of the hole, then a 20 MP camera with either FOV could be used, or a 5 MP camera with the FOV 2 could be used. However, a 5 MP camera with FOV 1 would not meet this requirement, nor would a 1 MP camera with either FOV.

2.1.9 Noise-Floor

Determine the acceptable noise-floor for all QOIs. Justify and document the criteria used to establish this acceptable noise-floor.

Tip 2.5 — Noise-Floor

This threshold of an acceptable noise-floor is application-specific, and is often determined by a subject matter expert. The noise-floor can be evaluated during the design of the measurement to aid in the selection of different DIC hardware (i.e. camera and lens, patterning technique, lighting) and processing parameters (e.g. subset size and step size for local DIC, and element shape function and element size for global DIC). See Sec. 5.4 for more information.

2.1.10 Frame Rate

Determine the desired frame rate.

Tip 2.6 — Frame Rate

There are several factors to consider when determining the desired frame rate, listed here in order of importance:

1. The most important factor in determining an appropriate measurement rate is the desired temporal resolution of the QOIs. Therefore, the frame rate for DIC measurements is chosen to be commensurate with the highest expected rate of variation of any QOIs. Because temporal resolution requirements are application-specific (see examples below), no general guidelines for frame rate and/or number of images to acquire during the test are given here.

   As an example, if the goal of the DIC measurements is to capture the yield point of a metal in a tensile test, then the temporal resolution requirements are a function of the number of frames required to adequately capture the elastic-plastic transition. Alternatively, if the goal is to determine the maximum strain before necking of a ductile material, the frame rate could be much slower. As a third example, if the test piece is cyclically loaded, the minimum frame rate is determined by the Nyquist-Shannon sampling theorem, which states that the image frame rate must be at least 2 times the frequency of oscillation; for noisy signals, a higher frame rate may be beneficial. See Fig. 2.5 for an illustration of these examples.

2. A second, minor consideration when selecting the frame rate is the amount of displacement between frames. If the displacement between frames is large, DIC algorithms may fail to locate the subset/element position in the deformed images. However, most DIC software allows for an initial guess (Sec. 5.2.9), which usually successfully compensates for large displacements between images. The maximum displacement between frames that can be captured is software-specific; however, a reasonable value (as a starting point) is approximately one subset/element size. For example, if the subset/element size is 25 px and the image scale is 20 px·mm^{-1}, then the maximum displacement between two sequential frames should be less than approximately 1.25 mm. If the velocity of the test piece is approximately 1 mm s^{-1}, then the minimum frame rate should be approximately 0.8 Hz.

3. A third, minor consideration is the amount of data collected during the mechanical test. Gigabytes of data can quickly be accumulated during DIC measurements, so good data management is essential.

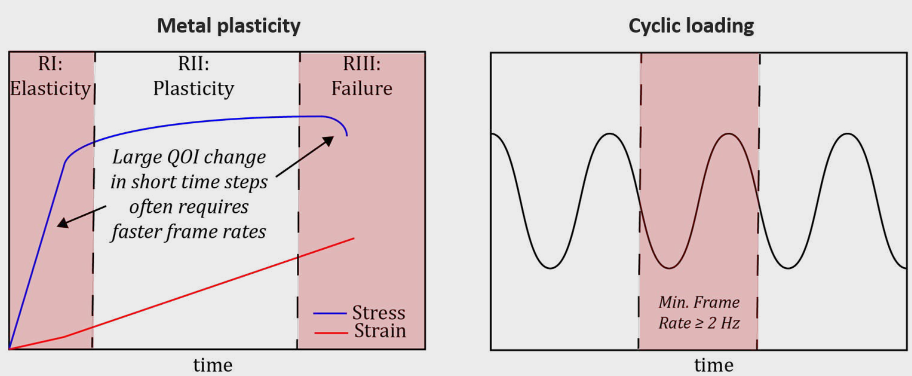


Figure 2.5: Two examples of factors to consider when determining the desired frame rate.

2.1.11 Exposure Time

Determine the maximum allowable exposure to limit motion blur.

Tip 2.7 — Motion Blur

The most conservative estimate for the maximum allowable test piece motion over the course of the exposure time is the noise-floor (Sec. 2.1.9) of the displacement measurements [1, Sec. 10.1.4]. For typical DIC setups, this threshold is around 0.01 pixels. In some fields such as machine vision, a threshold of 0.1 − 0.3 pixels is typically used, while dynamic modal tests often accept as much as 3 pixels of motion during the exposure time [17].[a]
The displacement, in pixels, per exposure is calculated as:

$$\begin{aligned}&\text{Displacement per Exposure [px]} = \\ &\left(\text{Velocity}\left[\frac{\text{mm}}{\text{s}}\right]\right)\cdot\left(\text{Image Scale}\left[\frac{\text{px}}{\text{mm}}\right]\right)\cdot(\text{Exposure Time [s]})\end{aligned} \tag{2.4}$$

[a]The recommended thresholds for motion blur given here in terms of pixels assume an ideal pattern feature size of 3–5 pixels (Sec. 2.3.2). An alternative view is that the motion blur should be below a percentage of the mean feature size. For example, if a pattern is imaged with a 1 MP camera and the feature size is 3 pixels, then motion blur of 0.3 pixels corresponds to 10 % of the feature size. If the same pattern is imaged with a 16 MP camera so that the feature size is now 12 pixels, the same amount of 10 % blur corresponds to 1.2 pixels. If the subset size is correspondingly increased in the second case, the blur should affect the displacement results similarly.

Tip 2.8 — Exposure Time and Frame Rate

While the exposure time is determined independently from the frame rate, the exposure time cannot be larger than the inverse of the frame rate (Sec. 2.1.10).

2.1.12 Synchronization and Triggering

Determine how the DIC images will be synchronized to other measurements of interest, such as applied force or displacement, strain gauges, thermocouples, etc. Determine how all data acquisitions will be triggered at the start of the mechanical test.[7]

2.2 Equipment and Hardware

2.2.1 Camera and Lens Selection

Select a camera and lens[8] pair to obtain the desired FOV, DOF, SOD, spatial resolution, temporal resolution and noise-floor determined in Sec. 2.1.

[7]The method used to synchronize DIC images with other measurements of interest is dependent on the specific hardware and software of the mechanical test; therefore, no further information is given in this guide.
[8]Some lenses have anti-vibration features, but the effects of these features on DIC measurements have not yet been thoroughly investigated.

Tip 2.9 — FOV, SOD, and DOF

FOV, SOD, and DOF are all intertwined and must be selected together. Cameras and lenses cannot be selected independently, due to the combined detector size and lens effect on the resulting image scale. For more information on the relationship between the FOV, lens focal length, camera detector size, and SOD, see Appendix B. Additionally, more information on camera and lens selection is found in [18, 19].

Tip 2.10 — Camera and Lens Selection

In most cases, experience is necessary to determine if a camera (e.g. noise level and dynamic range) or lens (e.g. distortions and resolution) is of sufficient quality for DIC. Some qualification or verification of new hardware is recommended, by characterizing the baseline noise-floor of DIC results with the new hardware. Typically, this is done by DIC vendors for any hardware they provide, but DIC practitioners can verify the results, or evaluate independent hardware, by using the procedures outlined in Sec. 5.4.2.

Recommendation 2.5 — Camera Selection

Typically, machine-vision, monochromatic cameras with nearly square pixels are used for DIC.[a] Also, detectors with global shutters (in which the data is read from all pixels simultaneously) are recommended over detectors with rolling shutters (in which the data is read from the detector row by row).

[a] The use of color cameras or the use of cameras that have pixels that are not square is possible; however, the use of these types of cameras requires complex analysis and is an advanced topic beyond the scope of the current edition of this guide.

Caution 2.3 — Camera Selection

Imaging systems that automatically adjust components of the lens and/or camera, such as auto-focus of the lens, or apertures that open/close with each image acquisition, are not appropriate for DIC measurements and should be avoided.

Caution 2.4 — Interlaced Frames

Some cameras (especially older digital video) have the ability to “interlace” frames to result in a smooth video that is more pleasing to the human eye. This feature combines every other row of the previous frame with the current frame, and is completely inappropriate for use in DIC.

Recommendation

When using new or unfamiliar camera hardware, it is recommended to verify that “interlacing” is not being used.

Tip 2.11 — Low Pass Filter

Some cameras have a physical low-pass filter element (also called an anti-aliasing filter) adhered in front of the detector. This is more typical of single-lens reflex (SLR) or digital single-lens reflex (DSLR) cameras than of machine vision cameras. It is important to know whether or not the camera being used for DIC has a physical low-pass filter, in particular when deciding whether or not to pre-filter the images, as described in Sec. 5.2.2.

Tip 2.12 — Lens Selection

There are two main types of lenses used for stereo-DIC (and occasionally used for 2D-DIC), either fixed focal-length lenses or zoom lenses. With a fixed focal-length lens, the FOV or image scale is adjusted by adjusting the SOD. With a zoom lens, the FOV or image scale can be adjusted by adjusting either the SOD or the focal length of the lens. Thus, zoom lenses can be more flexible than fixed focal-length lenses. However, because of increased complexity of the optics in a zoom lens, lens distortions are often larger for zoom lenses. Also, many (though not all) zoom lenses do not have a way of locking the adjustment of the focal-length ring, making them more susceptible to inadvertent changes if the camera/lens is moved.

Recommendation 2.6 — Telecentric Lens for 2D-DIC

If 2D-DIC must be used, a bilateral telecentric lens is recommended to mitigate small errors due to out-of-plane translation[20]; out-of-plane rotations and large out-of-plane translations, however, will still cause errors in 2D-DIC measurements. The magnitude of out-of-plane translations for which a bi-telecentric lens can compensate depends on the FOV.

If a telecentric lens is not available or feasible, it is recommended to use a long focal-length lens, to maximize the SOD, and hence minimize errors caused by out-of-plane motion (see Example 2.1).

Caution 2.5 — Telecentric Lens for stereo-DIC

Although a telecentric lens is recommended for 2D-DIC, telecentric lenses may not be used for stereo-DIC.[a]

[a] A telecentric lens may be used for stereo-DIC with a specialized camera model [21–23]. However, most commercial DIC software packages assume a pin-hole camera model, which is incompatible with telecentric lenses. Therefore, the use of telecentric lenses for stereo-DIC is an advanced topic and is outside the scope of this edition of the guide.

Recommendation 2.7 — Lock Moving Components on Lens

Lenses with the ability to lock moving components (e.g. focus ring, aperture ring, zoom setting (for a zoom lens)) are preferred, to reduce the likelihood of accidentally changing these components after they have been set to the desired position.

2.2.2 Camera and Lens Mounting

2.2.2.1 General Characteristics of Mounting System

Construct a sturdy camera and lens mounting system with the following general characteristics:

- Include sufficient degrees of freedom to allow for precise adjustment of the location and orientation of the camera(s)/lens(es) (i.e. translation or rotation stages, tripod adjustments, etc.).
- If the camera location and/or orientation need to be adjusted for calibration (Sec. 3.2.2.2), include the appropriate mechanisms in the mounting system (e.g. a bar that can rotate the camera(s) or a translation stage that can translate the camera(s)).
- Lock all moving components in the mounting system after the final position and orientation has been determined.

Tip 2.13 — Tape Moving Components on Lens

As mentioned in Recommendation 2.7, lenses with the ability to lock moving components (e.g. focus ring, aperture ring, zoom setting (for a zoom lens)) are preferred. However, if the only lens(es) available for the DIC measurement do not have locks for the moving components, masking tape can be used to lock the position of these adjustment rings. The rings should be taped after the imaging system is aligned and focused, but before the system is calibrated. Care must be taken during taping to not change the focus or other lens settings.

- For 2D-DIC, ensure the camera and lens optical axis is perpendicular to the surface of the test piece.

Caution 2.6 — 2D Out-of-Plane Errors

See Sec. 2.1.5 for more information about the implications of out-of-plane motion in 2D-DIC.

- For stereo-DIC, mount the cameras such that the desired FOV, image ROI, and stereo-angle are achieved. Recommendation 2.10 provides several considerations and recommendations regarding the orientation of the individual cameras and the stereo-rig.
- For stereo-DIC, mount both cameras rigidly together to avoid relative camera motion.[9] See Sec. 2.2.2.2 for more information on common types of mounting systems.

Caution 2.7 — Rigid Camera Mounting

Any relative motion of one camera with respect to the second camera will induce errors in DIC measurements.[a] If relative motion occurs, the camera system should be recalibrated.[b] To avoid this problem, rigid mounting is critical!

[a]If both cameras move together rigidly with respect to the test piece, only rigid-body DIC displacements are affected. For most applications where rigid-body motion is not important (e.g. strains are the QOI), this rigid-body displacement error is inconsequential.

[b]Rigid-body motion of the stereo-camera *pair* can be corrected in post-processing if there is a fixed reference point somewhere in the FOV. However, correcting for relative motion of one camera with respect to the second camera requires adjusting the extrinsic parameters of the calibration (Sec. 3.2). Some DIC software packages offer a "calibration correction" that corrects the extrinsic parameters of a stereo-camera system based on certain assumptions and minimization of the epipolar error (Sec. 3.3.2.2). However, this type of correction is beyond the scope of the current edition of this guide.

[9]Test setups in which the cameras cannot be practically rigidly-mounted together, e.g. large-scale tests with large camera separation that require individual tripods for each camera, are not discussed in this edition of the guide.

- Mount the combined camera/lens system near its center of mass. If either the lens or the camera is substantially more massive than the other, mount to the more massive element. Consider mounting at two places along the optical axis instead of just one, to minimize the lever-arm effect.

Recommendation 2.8 — Camera and Lens Mounting Orientation

Many commercial cameras, lenses, and mounts are designed to be used with the optical axis nearly horizontal. If the orientation of the optical axis is vertical, then verify the mounting, and reinforce it as needed to ensure the mount is effectively rigid in this orientation. Additionally, verify that the lens performs properly in this orientation, and that the focus or other settings do not drift.

Caution 2.8 — Camera and Lens Mounting Balance

Camera and lens systems that are not well balanced on their mounting are more likely to drift or become misaligned, thereby inducing errors into the DIC measurements.

- Stabilize and strain relieve camera cables to prevent the cables from pulling on the cameras or transferring ambient vibrations to the camera system. If the camera(s) will be moved for calibration (Sec. 3.2.2.2), ensure there is enough slack in the cables to accommodate the camera repositioning.
- Ensure that the camera support structure is stable. If necessary, add weights (e.g. sand bags) to tripods or other footing to prevent motion of the camera support structure.
- Minimize vibrations being transferred to the cameras.

Caution 2.9 — Vibrations

Any vibrations that are transferred to the cameras will directly increase the noise-floor of the DIC measurements. The amount of time and effort spent on minimizing vibrations is directly commensurate with the magnitude of the vibrations and the desired precision of the DIC measurements.

Tip 2.14 — Vibrations

Some vibrations — but not all — can be detected by the human eye by watching a live image stream, especially if the image is zoomed in so that individual pixels are visible. Camera and lens vibrations are more visible at larger SODs, and less visible for short SODs.

Caution 2.10 — Vibrations Invalidate Calibration

A vibrating stereo-DIC system can result in temporal changes in the orientation between the cameras that will invalidate the calibration, even if vibrations are not visible to the human eye.

Recommendation 2.9 — Minimizing Vibrations

To reduce the effects of vibrations, the following precautions are recommended:

- Ensure the cameras and mounting system are not in direct contact with any vibrating components (i.e. fan, compressor, hydraulics, test machine, lights, etc.) [24]
- Verify there are no vibrations being transferred through the floor. (Note that vibrations could come from equipment in other rooms in the building.)
- If vibrations are being transferred to the cameras, reinforce the mounting system and/or add damping.
- If the DIC measurement and test setup can accommodate different SODs and lenses of different focal lengths, use a shorter SOD and shorter focal-length lens.

Tip 2.15 — Epipolar Error

In stereo-DIC, the epipolar error is a good metric for indicating possible drift, misalignment, or vibrations in the camera/lens systems. For example, if the epipolar error of a series of static images was low immediately after calibrating the stereo system, but then increases over time, this could indicate drift of one or both imaging systems. If the epipolar error is cyclic over time, this could indicate vibrations affecting the imaging systems.

Recommendation 2.10 — Camera Orientation

The optimal camera orientation scheme depends both on the camera and test piece aspect ratios, as well as the direction of expected motion/ deformation during the DIC test (Fig. 2.6). In the following example, key concepts are illustrated using a tensile dog bone as the test piece.

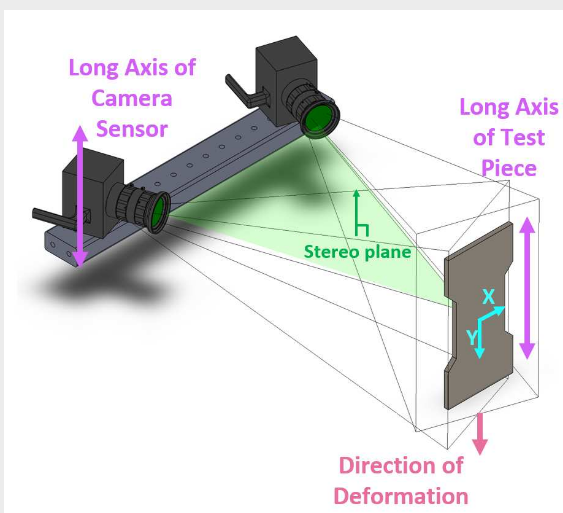


Figure 2.6: Schematic showing a setup for an example test piece (tensile dog bone) where the long axis of the camera detector is aligned both with the long axis of the tensile dog bone as well as the direction of deformation. Additionally, the long axis of the tensile dog bone is perpendicular to the stereo-plane (aligned with the normal of the stereo-plane).

Example

For example, a camera with an aspect ratio of 1920 px × 1200 px should be aligned with the greater number of pixels (1920 px) allotted to the longer side of a long and narrow test piece, as shown by the schematic with the green check mark in Fig. 2.7a. In Fig. 2.7b, the camera is rotated 90 degrees, and while the spatial resolution remains the same, much less of the ROI (here, the gauge length of a tensile dog bone) is captured in the FOV. Furthermore, many pixels are wasted on the outer edges of the image, not imaging the test piece. In Fig. 2.7c, the schematic shows the result of reducing the magnification to cover an entire ROI. However, the spatial resolution is now degraded, since there are only 1200 px along the test piece ROI, and a great number of pixels still are not imaging the test piece (again, wasted pixels).

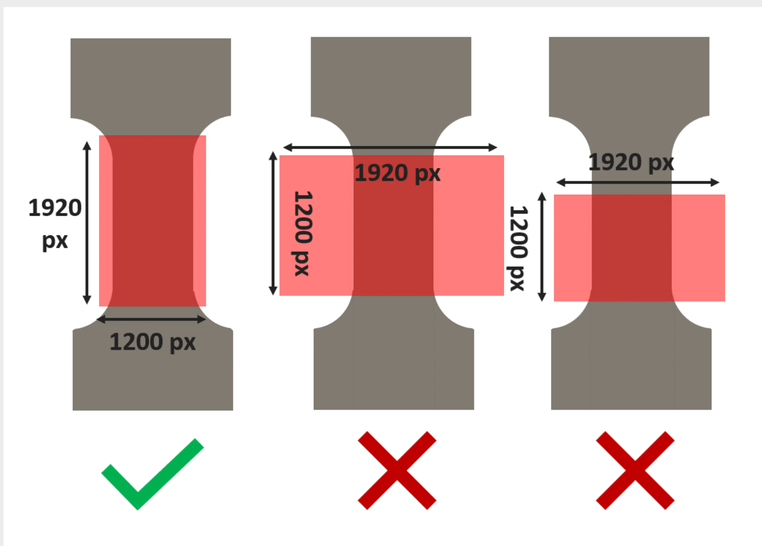


Figure 2.7: Schematics showing optimal (a) and non-optimal (b,c) orientations of a camera detector with a 1920 px to 1200 px aspect ratio with respect to a long and narrow test piece (here a tensile dog bone).

A second consideration involves the DOF. Both the initial undeformed test piece and the deformed test piece (or a test piece undergoing rigid body motion) should remain in the DOF envelope. For example, a tensile dog bone is long and narrow and when oriented as in Fig. 2.8a, will remain in the diamond shaped region where the DOF from the two cameras overlaps easily. However, if the tensile dog bone was rotated 90 degrees and deformed as shown in the Fig. 2.8b, the images would become increasingly more blurry and out-of-focus for one of the cameras on each side of the test specimen. This degradation of image quality could eventually cause the images to fail to correlate as the test piece progressed outside of the DOF.

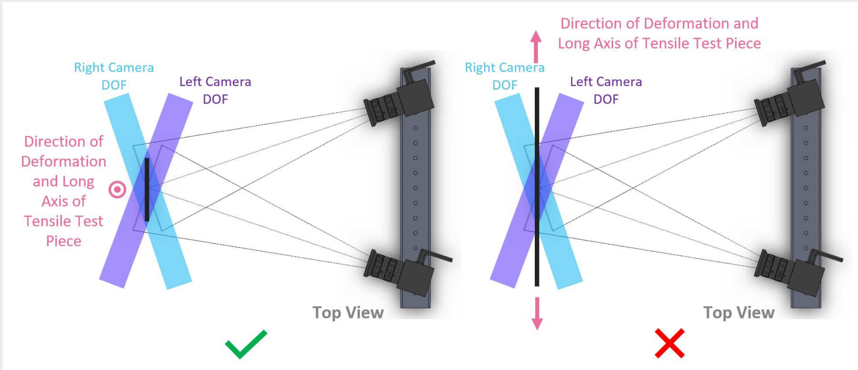


Figure 2.8: Schematics of an optimal (a) and non-optimal (b) orientation of a tensile dog bone test piece with respect to the DOF covered by a set of stereo-DIC cameras.

In summary, a set of recommended orientations for a tensile dog bone with respect to a non-square (rectangular) camera detector is given in Fig. 2.9; also included are two discouraged orientations that are inferior. As a final note, many cameras only feature mounting locations on one side of the housing, and as a result, the natural mounting location is not guaranteed to coincide with the ideal DIC setup. In these cases, adaptors, such as 90 degree angle brackets, may need to be employed to rotate the cameras.

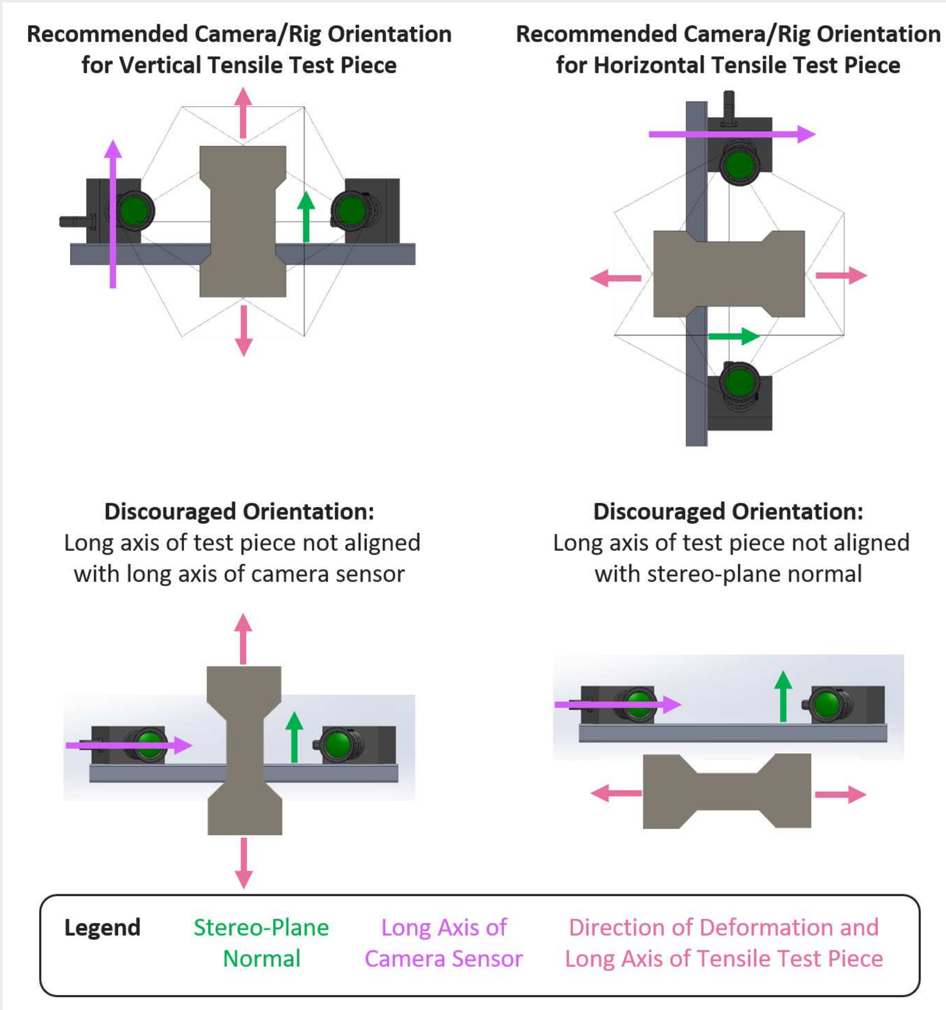


Figure 2.9: Summary of recommended and discouraged mounting configurations for the example of a tensile dog bone test piece (pulled axially).

2.2.2.2 Types of Mounting Systems

There are many types of mounting systems for camera(s)/lens(es) that are appropriate for DIC, and the selection of a mounting system depends on the mechanical test setup and components available in each laboratory. A standard mounting system, appropriate for a large range of mechanical test setups, is often available with the purchase of commercial, turn-key DIC systems. Alternatively, custom mounting systems can be built from commercially-available products. For mechanical test setups with complicated geometry, restricted access, or uncommon camera(s) and/or lens(es), mounting system components may need to be specially designed and fabricated. Some common types of commercially-available systems include, but are not limited to:

- Standard optical hardware, such as 1-1/2 inch (38 mm) posts and associated mounting hardware, bolted to an optical table.

- Sturdy tripods. For stereo-DIC, a single bar is either mounted at each end to a tripod or mounted to a single tripod at the center of the bar. The two cameras are then mounted to the bar. In this way, the cameras are mounted rigidly together, and not on independent tripods.[10]
- Studio stands. Camera mounting with studio stands is similar as mounting with tripods, but studio stands have two advantages. First, their base is weighted, decreasing the likelihood that sandbags or other weights will be necessary to stabilize the system. Second, they are designed with several lockable degrees of freedom, allowing for easy adjustment of camera location and orientation.
- Systems of bars pre-fabricated to varying lengths and associated assembly and mounting hardware.

2.2.3 Aperture

Select the aperture on the lens to obtain desired DOF (Sec. 2.1.7). For stereo-DIC, the aperture should be the same in both cameras (as close as possible).

Tip 2.16 — Lens Aperture, DOF, and Image Brightness

In addition to governing the DOF, the aperture of the lens also governs how much light enters the optical system. However, typically the aperture is chosen based on the desired/required DOF, and external light (Sec. 2.2.4) and exposure (Sec. 2.1.11) are adjusted in order to limit motion blur and obtain sufficient contrast. See Fig. 2.10 for an illustration of these lighting trade-offs.

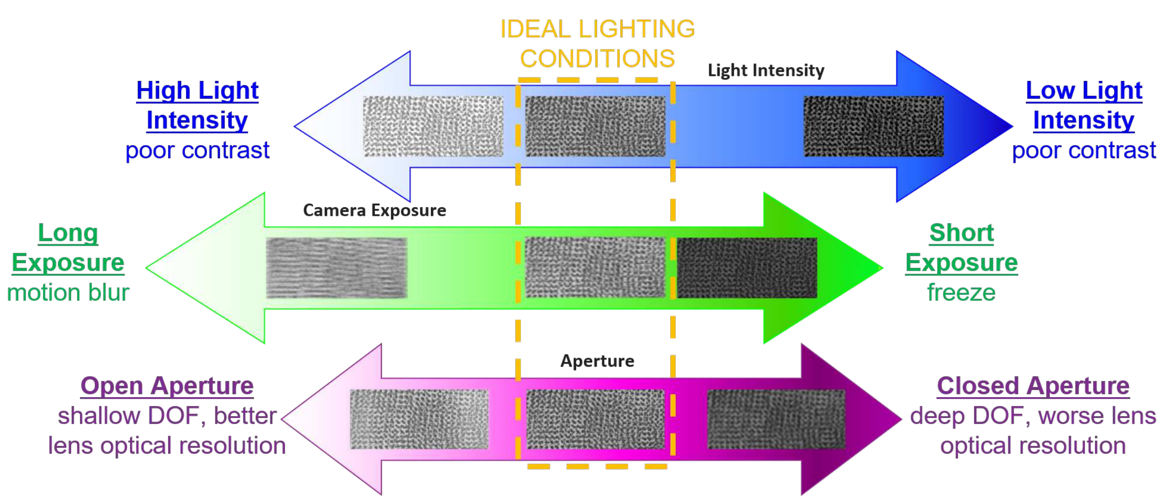


Figure 2.10: Illustration of lighting trade-offs regarding the light intensity, exposure time, and aperture.

[10] Refer to footnote 9 on page 20.

Tip 2.17 — Lens Aperture, DOF, and F-Stop Number

The smaller the aperture (the larger the f-stop number), the larger the DOF.

Caution 2.11 — Diffraction

Diffraction may become problematic at small apertures, while optical aberrations are accentuated by large apertures.

Recommendation

Moderate lens apertures are recommended, to avoid accentuated lens distortions or diffraction limits at extreme apertures [15]. The recommended aperture size or f-stop number is dependent on the lens and the application, but typically a value in the range of f/5.6–f/11 is recommended.

2.2.4 Lighting and Exposure

Given a pre-determined aperture (Sec. 2.2.3), select lighting and an exposure time (less than or equal to the maximum allowable exposure time, see Sec. 2.1.11) to have sufficient contrast between the lightest (white) and the darkest (black) regions of the DIC pattern. The contrast should be uniform over the entire ROI of the image, approximately the same in both cameras (for stereo-DIC), and constant in time. For standard stereo-DIC setups, the exposure time should also be the same for both cameras. See Fig. 2.10 for an illustration of lighting trade-offs. [11]

2.2.4.1 Type of Lights

Tip 2.18 — Lighting

In some cases (e.g. slow, quasi-static tests and moderate aperture), room lighting is sufficient. However, most of the time, additional lighting is required to have good contrast for a given aperture and exposure time. In these cases, white light or light of any wavelength or band of wavelengths will work.[a] (It is recommended, though, to avoid lighting that has significant intensity in the infrared range, as this may increase the temperature of the test piece, and thus change the behavior of the test piece.) The main requirement for lighting is that it is uniform and constant, both across the FOV and in time.

[a] Specific wavelengths of light can be advantageous over white light for some DIC measurements, but this is an advanced topic outside the scope of the current edition of this guide.

Recommendation 2.11 — Cross-Polarized Light

Cross-polarized light [25] or diffuse light (instead of focused or spot light) are recommended to reduce glare caused by specular reflections.[a] See Sec. 2.3.2.5 for more information about specular

[11] The exposure time is not strictly required to be the same in both cameras of a stereo-DIC setup. The exposure time may be adjusted for each camera independently to account for different sensitivities of the detectors, for instance, as long as each exposure time is short enough to limit motion blur as described in Sec. 2.1.11. However, this is an advanced topic outside the scope of the current edition of this guide.

reflections.

[a] Cross-polarized light is especially useful for curved surfaces or test pieces that are anticipated to undergo large rotations, but these topics are outside the scope of the current edition of this guide.

Caution 2.12 — Light Flicker

Some lights may flicker (i.e. change intensity) at the same frequency as the alternating-current (AC) electrical supply (typically 50–60 Hz). Similarly, for some LED lights, the intensity of the light is controlled by varying the duty cycle of the light, again typically at 50 Hz. In either case, if the imaging frequency (i.e. frame rate) is close to or faster than the AC electrical supply frequency or the duty cycle frequency, then the intensity of the light (and thus the contrast of the images) can vary between images.

2.2.4.2 Light Mounting

Tip 2.19 — Lighting Adjustments between Calibration and Test

Often, different lighting and/or exposure is required to have good contrast for the test piece versus a calibration target (see Sec. 3.2 for information on DIC system calibration). Adjusting the light intensity, position, and/or the exposure time for calibration purposes is a common procedure and is acceptable as long as the camera, lens, and mounting are not disturbed (see Sec. 3.2.2.3), and the adjustments are reversed before the DIC measurements are made.

Recommendation 2.12 — Light Mounts

Numerous vendors supply lights that are integrated robustly onto the camera mounting system; these systems are designed to allow adjustment of the lights without disturbing the cameras. Alternatively, lights can be mounted on a separate frame than the cameras, or remote lighting control can be used, to reduce the possibility of unintentional camera motion when adjusting lights.

2.2.4.3 Contrast, Intensity, and Gain

Recommendation 2.13 — Image Contrast

Because DIC metrological properties rely highly on image gradients (and thus contrast), the better the contrast is (without the image being overexposed or underexposed), the less noisy the DIC results are. For an 8-bit camera, the minimum contrast to have a displacement noise-floor of around 0.005 pixels is approximately 20% (50 grey-level counts between the light and dark features) [26], though contrast of at least 50% (130 counts) is typically preferred.[a]

[a] More advanced users may optimize the contrast beyond simply the difference between the light (white) and dark (black) intensities. A well-spread distribution of intensities between these limiting white and black values behaves better than a bi-modal distribution. It can be advantageous to use only the lower portion of the dynamic range of the camera detector, as long as there is still sufficient contrast, because camera noise typically scales with intensity (though this can be camera-specific) [27].

Tip 2.20 — Image Contrast

There can be sufficient contrast in the image for DIC, even if the images "look" dark to the eye. This is especially true for camera detectors having larger dynamic ranges.

Caution 2.13 — Evolution of Image Constrast

Contrast may change during the test, as the test piece is moved and/or deformed. Therefore, ensure there is sufficient contrast both at the beginning and throughout the duration of the test. Pre-testing extra test pieces may be required to confirm lighting and contrast throughout the test.

Recommendation

If the mean contrast in the image changes over time during the test, the zero-mean normalized sum of square difference (ZNSSD) matching criterion is recommended to compensate for contrast changes.

Caution 2.14 — Underexposure, Overexposure, and Glare

Ensure no regions-of-interest of the image are overexposed (i.e. the intensity at every pixel should be less than the maximum of the camera) or underexposed (i.e. the intensity at every pixel should be greater than the minimum of the camera), and there is no glare in the ROI. See Fig. 2.16 and Fig. 3.2. These conditions should be true both initially and as the test piece is translated and rotated within the expected 3D volume of motion and/or deformation [28]. In stereo-DIC, check both images for glare, as glare could appear in only one of the two cameras. Keep in mind that glare can manifest as either points or as lines.

Caution 2.15 — Camera Gain

Do not increase the gain (sometimes referred to as the exposure index or the "ISO setting") of the camera(s) — the conversion between the number of electrons recorded by the detector and the number of counts in the gray-level intensity — in an attempt to increase the contrast or intensity. Increasing the gain increases camera noise, with no benefit for DIC [29].

2.2.5 Hardware Heating

Caution 2.16 — Hot Lights

Almost all cameras and lights become hotter than room temperature when run continuously, even "cool" LED lights. Hardware heating can negatively impact DIC measurements in several ways, including but not limited to:

- Changing the sizes and positions of the camera detector(s) and lens(es) due to thermal expansion of the components of the camera(s) and lens(es).
- Heating of the mounting structure, which, in stereo-DIC, can result in a change in the relative positions of the cameras during testing that negates the calibration.

- Inducing convective air currents (known colloquially as "heat waves") that refract light between the test piece and the imaging system.[a]

[a] Heated test pieces may also induce heat waves, but heated test pieces are excluded from the scope of the current edition of this guide, and are not discussed further.

Recommendation 2.14 — Camera Warmup

To mitigate effects of thermal expansion of the camera(s), lens(es) and mounting structure, cameras should be turned on and operated at the target frame rate (Sec. 2.1.10) until they have reached a stable operating temperature. Calibration images and DIC measurement images should only be acquired after the cameras have reached thermal equilibrium. See Sec. 3.1.3 for more information on warming up the cameras.

Tip 2.21 — Heat Waves / Mirage Effect

Even small temperature changes can cause heat waves or the mirage effect between the test piece and the imaging system, which refract light and cause errors in DIC measurements. These errors manifest as spatially- and temporally-varying "fingers" in the displacement and strain fields (Fig. 2.11) that, when animated in a movie, can look similar to flames in a fire [30].

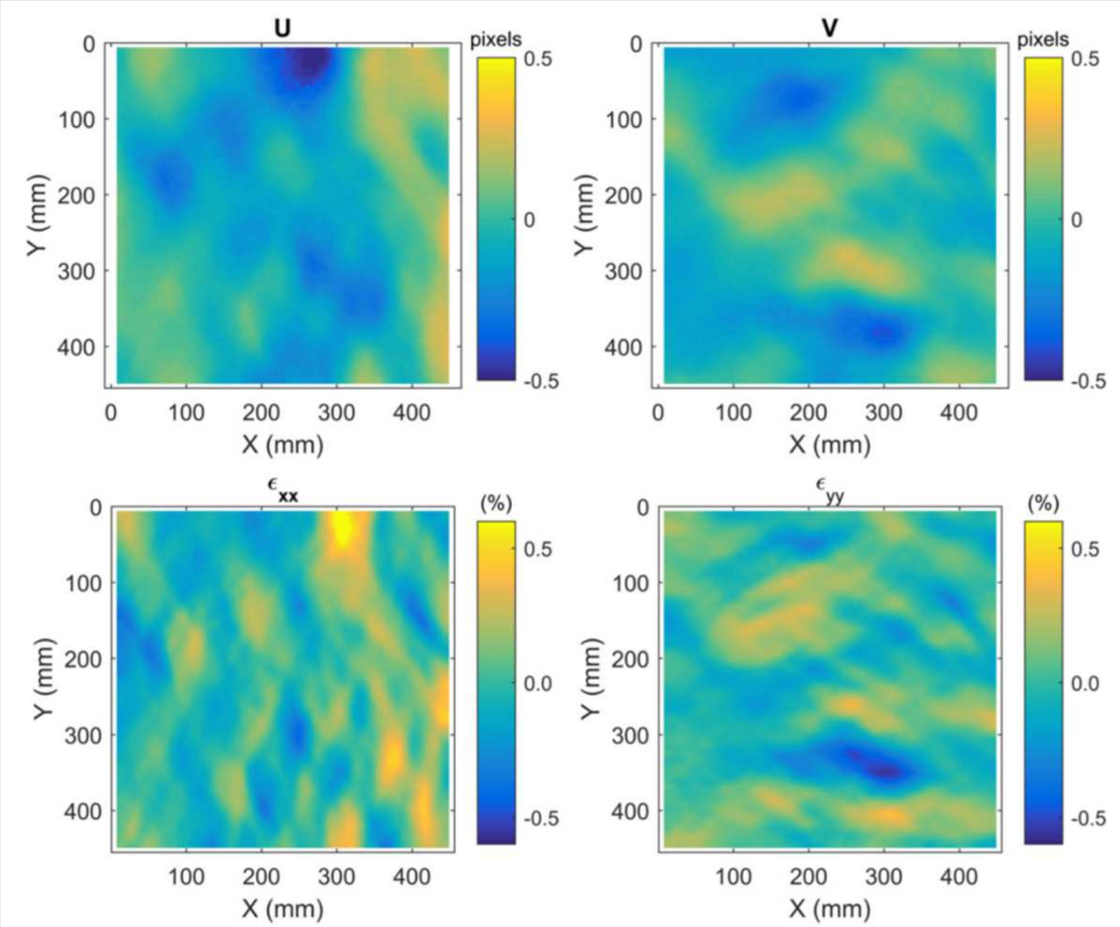


Figure 2.11: Illustration of the "fingers" that appear in DIC data as a result of imaging through heat waves, for the horizontal and vertical in-plane displacements, U and V, and the horizontal and vertical normal strains, ε_{xx} and ε_{yy} [30].

Recommendation 2.15 — Heat Waves / Mirage Effect

Because errors caused by heat waves or the mirage effect are not easily filtered in post-processing [30], it is strongly recommended to minimize heat waves in the test setup before images are acquired, using one or more of the following preventative steps. Similar to camera vibrations (Sec. 2.2.2), the amount of time and effort spent on minimizing heat waves is directly commensurate with the magnitude of the errors caused by heat waves, and the desired precision of the DIC measurements.

- Mount lights *above* and *behind* the camera(s) if possible. Avoid mounting lights between the camera(s) and the test piece. In particular, avoid mounting lights below the camera/test piece plane.

- If lights are the source of heat waves and the test duration is short, keep lights off as much as possible to prevent them from heating up, and turn them on only for the test duration. If the test duration is long, strobe the lights on only when images are being acquired, or add a fan onto the lights to cool them and homogenize the air temperature.
- If heat waves are caused by the camera(s), cool the camera(s) with a heat sink or a fan. Alternatively, place an air knife in front of the cameras, to homogenize the air between the cameras and the test piece without blowing air directly onto the camera(s).

Caution 2.17 — Fans

Beware of inducing camera motion by blowing air onto the camera(s) and/or transferring vibrations from a fan to the camera mounting structure. If using a fan to cool lights or camera(s), ensure that the reduction in errors due to reducing heat waves is more impactful than any increase in errors due to camera motion.

2.3 DIC Pattern

2.3.1 Type of DIC Patterns

One fundamental assumption of DIC is that the motion and deformation of the pattern that is imaged exactly replicates the underlying test piece motion and deformation. Sometimes, images of the surface of the test piece itself have a sufficient natural pattern that is adequate for DIC, and no artificial pattern needs to be applied.

Tip 2.22 — Natural DIC Pattern

As a first step, the test piece surface can be imaged, and the natural pattern can be evaluated to ascertain if it has the characteristics described in Sec. 2.3.2. If so, no applied DIC pattern is necessary.

Caution 2.18 — Surface Coating on Test Piece

Be cognizant of any surface coating that may be on the surface of the test piece, i.e. brittle mill scale on steel, brittle oxides, added coatings such as zinc coating on steel, etc. Such surface coatings may or may not move with or behave like the underlying material. Ensure that the pattern being imaged on the surface reflects the deformation of interest of the bulk material underneath.

Most of the time, a pattern must be applied to the test piece surface. Typically, though not exclusively, applied patterns consist of roughly circular "speckles" of a (preferably) uniform size but random locations.[12]

[12] More advanced "optimized" pattern designs are outside the scope of the current edition of this guide, but information can be found in [31–33]. Additionally, some DIC manufacturers prefer a regular (not random) pattern, but these are also not covered here.

Recommendation 2.16 — Evaluation of DIC Pattern

The quality of a DIC pattern is often evaluated by manual, visual inspection of the images, where the DIC practitioner looks for the characteristics described below. More quantitative evaluation of a DIC pattern is typically not necessary outside of research activities, but can consist of metrics such as image gradients to evaluate contrast, and other image morphology methods to evaluate feature edges, shapes, sizes, and distribution [34, 35].

2.3.2 General Characteristics of DIC Patterns

Both natural and applied patterns should have the following general characteristics:

2.3.2.1 Size

The optimum pattern feature size is 3–5 pixels [1, Sec. 10.1.3.1], [15, 36]. This guideline applies to both the light (white) and the dark (black) features.

Tip 2.23 — Camera-Limited Vs. Lens-Limited Spatial Resolution

The guidelines for pattern feature size of 3–5 pixels assumes the overall spatial resolution of the optical system is limited by the camera, which is the case for most DIC applications. However, at high magnification (small FOVs) or large image size, the system may be lens-limited, and larger pattern feature sizes may be required [15]. See Tip 2.4 for more details.

Tip 2.24 — Measuring Pattern Feature Size

There are many definitions of feature size and many methods of determining feature size [1, Sec. 10.1.3.1], [33, 36]. However, a rough, manual estimate, in which the DIC practitioner zooms in on an image and approximates the feature size by eye, is typically sufficient, as shown in Fig. 2.12.

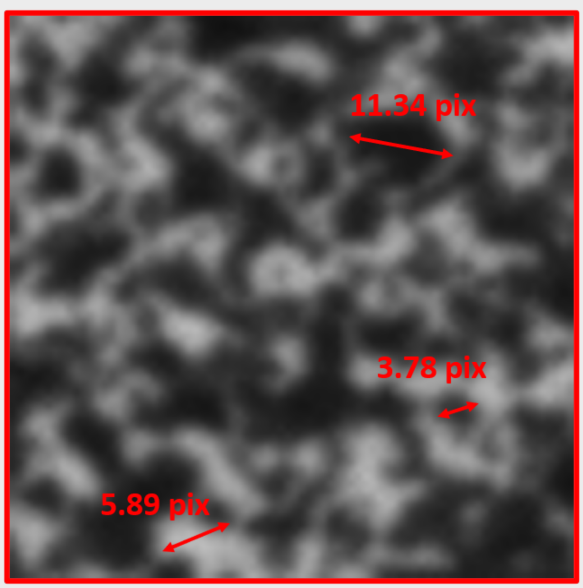


Figure 2.12: Illustration of a manual estimate of of the feature sizes of a DIC pattern. Note, both black and white features should be between 3–5 px.

Caution 2.19 — Aliased Pattern Features

Pattern features that are smaller than 3 pixels risk being aliased and adding error to DIC results [1, Sec. 10.1.3.1], [15, 37, 38]. A visualization of how an aliased pattern appears in a digital image is shown in Fig. 2.13. This error is more pronounced when displacements are small, due to a lower signal-to-noise ratio. In the case of a compression test, features that started at the lower end of the recommended range (e.g. 3 pixels) may become aliased as the pattern is compressed and the features and spacing are reduced. Features that are larger than necessary (i.e. larger than 5 pixels) will require larger subsets/elements (see Sec. 5.2.6) and thus will degrade spatial resolution of displacements and strains, but will otherwise not negatively effect the results (i.e. will not add noise).

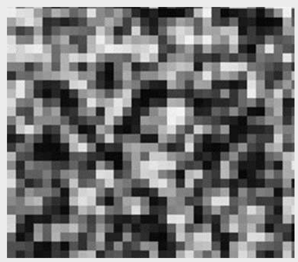


Figure 2.13: Photo showing how an aliased pattern appears in a digital image.

Recommendation

For many applications, if the selected patterning method results in a wide spread of feature sizes, then it is generally preferred to use features that are larger than optimal, to limit the number of aliased features. That is, added noise due to aliased features is typically worse than degraded spatial resolution due to large features.

Tip 2.25 — Physical Pattern Feature Size

The physical pattern feature size is determined based on the image scale. For example, given an image scale of 20 pixel mm^{-1}, a target size of 5 pixel features translates to a physical size of (5 pixel)/(20 pixel mm^{-1}) = 0.25 mm.

Note that the physical feature size required for a given DIC measurement depends on both the FOV and the image size. For a given FOV and lens, a camera with a smaller image size (e.g. 1 MP camera) will require larger features and spacing than a camera with a larger image size (e.g. 12 MP camera).

Recommendation 2.17 — Pattern Feature Size Variation

In stereo-DIC, where the cameras are at an angle to the test piece, the image scale (on the surface of the test piece) is not constant over the FOV of each camera. To ensure that the smallest DIC pattern feature is not aliased at any location in the ROI of either camera, consideration must be given to the changing image scale across the ROI. Therefore, the location in the ROI, of either camera, where the image scale is smallest should be found and used to define the smallest allowable DIC pattern feature.[a]

[a]More advanced users may take the varying image scale into account when designing an optimized DIC pattern. However, this advanced topic is outside the scope of the current edition of this guide.

Tip 2.26 — Confirming Pattern Feature Size

After the desired physical size of the DIC pattern features is calculated based on the image scale, the desired physical size can be confirmed by printing a synthetic pattern on paper using a standard office printer (if the printer has sufficient resolution for the desired pattern size) and imaging the pattern using the same optical system as the actual test, to ensure all features are 3–5 pixels in size.

2.3.2.2 Variation

The pattern should have sufficient random variation such that subsets/elements in different regions of the image can be uniquely identified, as shown in Fig. 2.14.

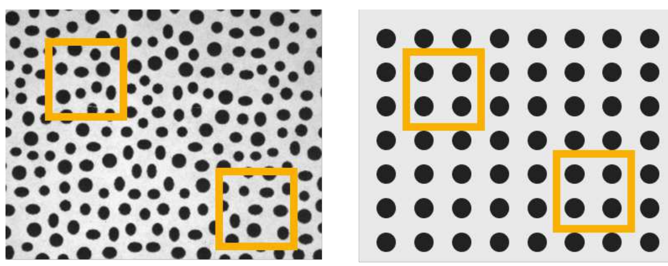


Figure 2.14: Illustrations of random versus regular patterns. The yellow boxes represent subsets/elements.

Caution 2.20 — Regular Patterns

Oriented regular (anisotropic) patterns can be problematic for many DIC systems, and should be avoided unless motion in only one direction is required. For example, a pattern based on a series of periodic lines of different widths can result in correlation of motion normal to the lines, but with no correlation of motion parallel to the lines.

Recommendation

If a regular pattern (e.g. repeated printed pattern) is used, then some randomization should be added in addition to the pattern (e.g. adding some random marker dots to the printed pattern, or varying the width of regular periodic lines).

2.3.2.3 Density

Pattern density should be approximately 50 % (i.e. there should be approximately the same area of light (white) and dark (black) pixels in any intended subset/element of the ROI of the image) [1, Sec. 10.1.3.1], [39]. If round speckles are used, then a density closer to 25–40 % can be expected due to the required minimum spacing between the round speckles. Examples of pattern density are shown in Fig. 2.15.

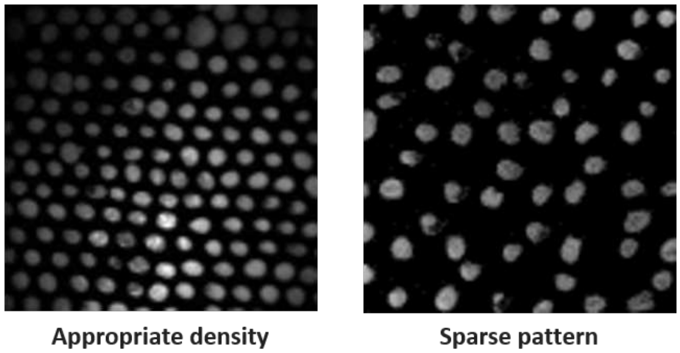


Figure 2.15: Images of a DIC pattern with appropriate or low (sparse) density.

2.3.2.4 Quality

Pattern quality degradation should be minimized and not permitted to result in decorrelation during the analysis.[13]

Tip 2.27 — Degradation of Natural Patterns

For natural DIC patterns, sources of pattern degradation include, but are not limited to, significant morphological changes and development of slip bands on the surface of the test piece during plastic deformation.

For applied DIC patterns, sources of pattern degradation include, but are not limited to, fading, cracking and debonding.

Tip 2.28 — Verification of Pattern Quality

Pretesting of extra test pieces may be required to verify the suitability of a pattern throughout the duration of the test.

Tip 2.29 — Measurement Uncertainty due to Pattern Degradation

Even at strains where decorrelation does not occur, pattern degradation can result in reduced correlation quality and increased uncertainty in the measurement [35].

[13] Note that in tests involving large deformation (e.g. several hundred percent deformation in elastomers), a well-bonded applied pattern may deform so much that correlation is lost between the first image and an image later in the test, even if it does not debond or crack. In this case, incremental correlation may be used. This situation of large deformation, however, is outside the scope of the current edition of this guide and will not be discussed further.

2.3.2.5 Reflections

The pattern sheen should be matte and not glossy, to avoid glare and specular reflections, as shown in Fig. 2.16.

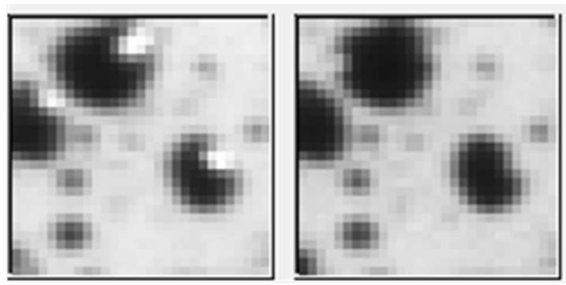


Figure 2.16: Examples of specular reflections on glossy speckles versus a matte pattern with no glare or reflections.

Caution 2.21 — Specular Reflections

Specular reflections can often be hidden in an otherwise good DIC pattern (i.e. appearing as artificial bright spots in one or both of the camera images). Specular reflections are dependent on the orientation and position of the test piece with respect to the light source and camera, and can change if the test piece is rotated or translated. Additionally, in stereo-DIC, specular reflections often look different in each camera, which effectively makes the DIC pattern different and uncorrelated in each FOV. Therefore, specular reflections should be avoided.

Recommendation 2.18 — Cross-Polarized Light

To reduce specular reflections, use cross-polarized light, or diffuse light, as described in Recommendation 2.11 in Sec. 2.2.4. If specular reflections cannot be sufficiently minimized through the lighting, a photographic dulling spray can be applied to the DIC pattern. However, if a dulling spray is used, the DIC pattern should be carefully evaluated, to ensure that the spray does not degrade the pattern.

2.3.3 Characteristics of Applied Patterns

Applied patterns, regardless of the method used to create them (i.e. painting, applying an adhesive-backed foil or sticker, stamping or drawing with ink, applying a powder, transfer printing, etc.), should have the following additional characteristics, which do not necessarily apply to natural patterns.

Recommendation 2.19 — Mask Gripping Region

For tensile tests, before applying a pattern to the test piece, mask the grip sections so that the pattern is not applied to the areas of the test piece that will be gripped in the load frame. This will help increase grip force, reduce likelihood of the test piece slipping within the grips, and prevent clogging of the grips with the pattern material (e.g. paint).

2.3.3.1 Compliance

The applied pattern should be thin and compliant relative to the test piece, such that it does not change the test piece behavior being measured during the test.

Caution 2.22 — Pattern Compliance

If the applied pattern is thick and/or stiff compared to the test piece, the DIC measurements based on images of the pattern may reflect the deformation of the applied pattern, rather than the deformation of the underlying material of interest.

2.3.3.2 Bonding

There should be good bonding between the test piece and the applied pattern.

Recommendation 2.20 — Cleaning the Test Piece

Before applying a DIC pattern, clean the test piece to promote good bonding between test piece and pattern. For example, for common metals (e.g. steel and aluminum), acetone can be used first to remove grease, cutting fluid, ink, etc. However, acetone leaves a residue after evaporating, so test pieces cleaned with acetone should always be subsequently cleaned with a solvent that does not leave a residue, such as isopropanol.

Additionally, if the surface is very smooth, consider roughing it with sand paper to promote adhesion of the applied pattern to the test piece surface, if such treatment will not alter the test piece properties.

Caution 2.23 — Pattern Debonding

Debonding of an applied pattern can be an insidious problem. In some cases, an applied pattern may locally debond from the test piece, yet remain intact and continue to deform independent of the test piece. In these cases, the fact that the pattern debonded may not be obvious. Some examples of pattern debonding and degradation are shown in Fig. 2.17.

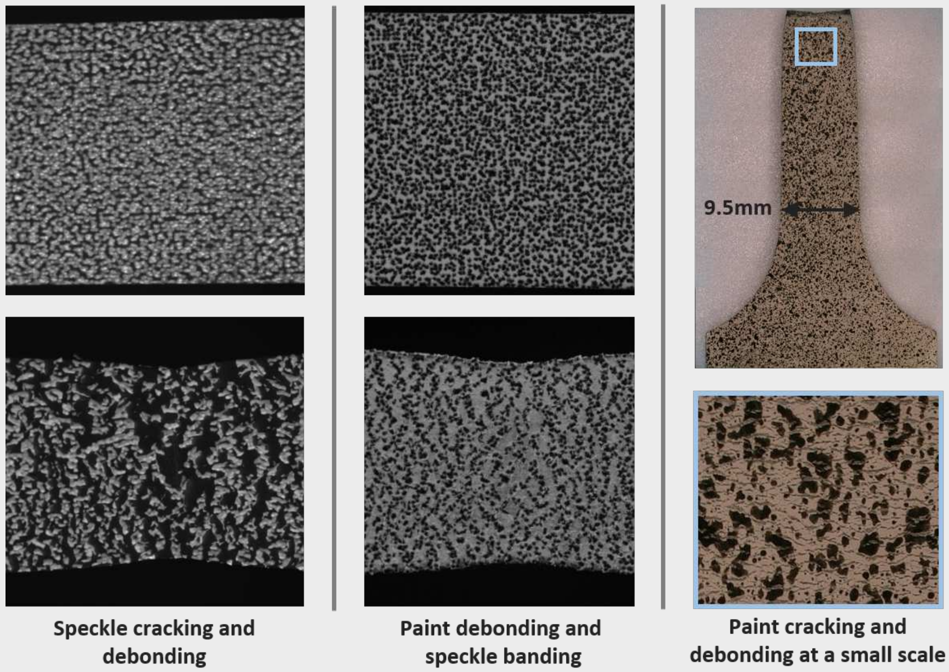


Figure 2.17: Examples of different debonding-related pattern degradations.

Recommendation

Inspect the test piece and applied pattern closely after the test, to look for any indications or evidence of pattern debonding.

2.3.3.3 Fidelity

The applied pattern should move and deform conformally with the test piece surface.

Tip 2.30 — Paint Ductility

For paint-based patterns, the ductility of the paint should be aligned with the expected deformation. That is, for test pieces that are expected to undergo large deformation, the paint should be as ductile as possible, so that it stretches with high fidelity with the underlying test piece without cracking or debonding. To accomplish this, the test should be carried out immediately after painting. Alternatively, individual features (e.g. speckles) can be placed directly on the test piece, without a base coat of paint.

On the other hand, if the test piece is brittle and observation of crack propagation is important, the paint should be as brittle as possible, while still not debonding or cracking independent of the test piece, so that the paint cracks at the same time as the test piece. In this case, the paint should be allowed to fully cure, and can even be baked (if baking does not alter the test piece properties) to make it more brittle. Alternatively, individual features (e.g. speckles) can be placed directly on the test piece, without a base coat of paint, so that cracking of the test piece can be observed directly.

If no base coat is used, and individual features are placed directly on the test piece, ensure that there is sufficient contrast and that there are no specular reflections (see Sec. 2.3.2.5).

Caution 2.24 — Laser Speckle Patterns

Sometimes, inexperienced DIC users think that an interference-based laser speckle pattern would produce a good pattern for DIC. However, this type of pattern will decorrelate from the motion of the test piece for large displacements, and is not recommended for DIC.[a]

[a]There are limited conditions in which a laser speckle pattern can be used for DIC, but this is an advanced topic that is outside the scope of the current edition of this Guide.

2.3.3.4 Thickness

The pattern should be of uniform thickness.

Caution 2.25 — Pattern Thickness

In stereo-DIC, a pattern with a rough surface can result in the same portion of the pattern appearing substantially different between the left and right camera images, which can hinder cross-correlation between the two images. In 2D-DIC, a pattern with areas of different thicknesses can result in artificial strain gradients across the transitions between the areas of different thicknesses.

2.3.4 Patterning Techniques

There are many different techniques available to create appropriate patterns for DIC, such as stencils, stamps, incomplete layers of paint (either using a commercial spray paint can, or using an air brush), and printer toner or other fine powders, to name a few. Patterning techniques are limited only by the imagination. Often, patterning techniques are learned through on-the-job training by more experienced DIC practitioners, through training by a vendor when a new DIC system is purchased, or through classes taught by subject-matter experts.[14] Due to the immense variety and nuances of patterning techniques, no guidelines are given here concerning the execution of specific patterning techniques.

Tip 2.31 — Library of Patterning Techniques

In order to facilitate the design of DIC measurements, creation of a table of patterning techniques and the resulting pattern size is recommended for each DIC practitioner or laboratory. Additionally, a library of physical chips with patterns created with different techniques is helpful when designing a new DIC measurement, because the size and contrast of different patterns can be quickly evaluated with the preliminary camera, lens, and lighting setup.

Tip 2.32 — Verification of Patterning Technique

Once a patterning technique has been selected, pattern a scrap test piece and image the pattern to verify that the pattern has the right size, shape, distribution and density. Images should be taken in the test setup or in a mock setup that uses the same cameras, lenses, SOD, stereo-angle, etc. as the actual setup. The scrap test piece should be the same material as the actual test

[14]iDICs offers DIC classes at their annual conference. For more information, see www.idics.org.

piece of interest, as patterning techniques can produce different results on different materials. (For example, spray-paint speckles may be larger on metal, where the paint droplets spread out, than on cardboard or paper, where the paint droplets soak into the material.)

3 — Preparation for the Measurements

3.1 Pre-Calibration Routine

3.1.1 Review of Test Procedure

Before preparing for and executing the mechanical test with concurrent DIC measurements, review the overall test procedure:

- Evaluate the tentative testing procedure to be used, and ensure that no steps in the procedure that occur after a test piece has been patterned, but before it will be tested (e.g. gripping or assembly), will damage the pattern. Modify the testing procedure if necessary to reduce the likelihood of scratching or contaminating the pattern (e.g. oil on the surface of the test piece).
- Ensure the mechanical load frame is properly adjusted and calibrated.
- Review the time line of the test process and ensure there is adequate time for all steps, such as warming up the cameras, warming up the load frame (if necessary), calibrating the DIC system, reviewing the calibration, preparing and patterning the test piece, testing the test piece, etc. Determine at what point in the test process the test piece should be patterned (if using an applied pattern).
- Ensure environmental conditions (e.g. temperature) will be stable during the course of the DIC calibration and mechanical test.[15]
- Consider adding a stationary backdrop behind the test piece, to prevent any people or objects moving behind the test piece from adversely affecting the images.

3.1.2 Cleanliness of Equipment

Ensure there is no dirt, dust, or other foreign particles (e.g. water, marks, oil, smears, fingerprints) on lens, camera detector, or calibration target.

Recommendation 3.1 — Clear Lens Filter

Keeping a clear lens filter (or linear polarizer if using cross-polarized light) on a lens as a semi-

[15] This consideration is more important for outdoor testing, though outdoor testing is outside the scope of this edition of the guide.

permanent addition to the lens protects the lens and makes cleaning easier. When lenses and cameras are not in use, lens caps and body caps should be used to protect the equipment. Store calibration targets in protective cases to keep them from getting dirty or damaged.

Recommendation 3.2 — Evaluating Cleanliness of Equipment

Image a white sheet of paper or other bright, solid background and look for any blurred spots or smears that could indicate dirt in the optical system (see Fig. 3.1). The image may need to be digitally magnified until individual pixels are visible. Because the sheet of paper may not be perfectly clean itself, translate the sheet. If the spots/smears move with the paper, then the dirt is on the paper; if the spots/smears remain stationary, then the dirt is somewhere in the optical system. To determine if dirt is on the lens or detector, rotate the lens. If the dirt rotates with the lens, the dirt is on the lens; otherwise, if the dirt remains stationary while the lens is rotated, the dirt is on the camera detector. Additionally, the external surface of the lens and the camera detector (with the lens removed) may be visually examined for the presence of dirt.

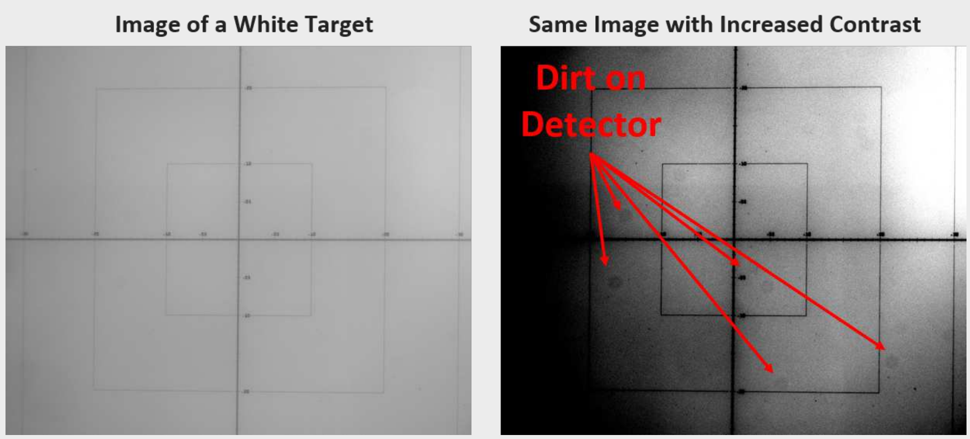


Figure 3.1: Image illustrating dirt on the detector and/or lens, when viewing a white target. Left: Original image contrast (i.e. intensity scaled across the full dynamic range of the image), where dirt is not easily visible. Right: Enhanced image contrast, clearly showing multiple specs of dirt.

Tip 3.1 — Cleaning Camera Detectors and Lenses

Often, pressurized air, such as canned air or a bellows-type or bulb-type blower, is sufficient to remove dust or particles from the lens or detector. If canned air is used, the bottle should be kept upright and not shaken, to prevent propellent or condensate from being expelled from the can. Also, the canned air should first be sprayed away from the lens or detector, to ensure that no propellant or condensate is being emitted. Another tool that can be used to remove dust or particles is an optics cleaning brush.

To remove other contaminants such as oil, fingerprints, etc., lens paper and alcohol-based lens cleaning solution can be used to clean lenses. There are also specific products made to clean camera detectors, which consist of a swab that matches the camera detector size, and an appropriate cleaning fluid. Do not use denatured alcohol (also called methylated spirits) to clean a lens or detector; denatured alcohol can contain up to 4 % water, which, while evaporating, can bind dirt onto the lens or detector. Always follow manufacturer's instructions for cleaning lenses or camera detectors.

Caution 3.1 — Cleaning Camera Detectors and Lenses

Anytime the optical system is exposed (e.g. lens caps and/or body caps are removed and/or the lens is removed from the camera), be careful not to introduce dirt into the optical system. Be very careful when cleaning a lens or camera detector, as they can be easily, and irrevocably, damaged!

3.1.3 Camera Warm-Up

Turn on the camera(s) and acquire images at the target frame rate (Sec. 2.1.10) to allow them to warm up to a stable operating temperature. The camera(s) should be at a stable operating temperature before any calibration or DIC measurement images are acquired. Refer to the DIC vendor manual for more information for vendor-supplied cameras.

Tip 3.2 — Camera Warm-Up

The time required for a camera to warm up to a steady temperature depends on the camera and laboratory environment, as well as the acquisition rate of the images. Moreover, the camera temperature rises some when a live feed is shown, but increases further when images are actually being acquired. Typically, warm-up times range from several minutes to several hours. Before using a new camera for DIC, monitor camera temperature during the warm-up period in the expected (or similar) laboratory environment, while acquiring images at the desired acquisition rate, and note the time required for the temperature to plateau. Use this warm-up time for all future DIC measurements that utilize that camera and that acquisition rate. If the acquisition rate is changed, the warm-up time will need to be re-computed.

Caution 3.2 — Camera Warm-Up

If the cameras are not warmed up, errors can be introduced into DIC results due to thermal expansion of the cameras and lenses [40], and due to drift induced by thermal expansion of the camera mounts. See Sec. 2.2.5 for more information.

3.1.4 Synchronization

For stereo-DIC measurements, ensure the two cameras are synchronized to each other. For either 2D-DIC or stereo-DIC, review the data acquisition plan, and ensure any external signals (i.e. force, extensometers, strain gauges, etc.) are synchronized with the DIC camera(s).

Caution 3.3 — Camera Synchronization

Synchronization of the cameras in stereo-DIC is critical! Delay between the two cameras will result in errors in the DIC measurements.

Tip 3.3 — Camera Synchronization

Synchronization of the two cameras can be verified in many different ways, including:

- Image a moving test piece that has a DIC pattern, correlate the images in the DIC software, and verify that the epipolar error is acceptable based on the DIC software documentation.
- Image a strobe light set to the same frequency as the image acquisition frequency.
- Image a dynamic event and ensure the event occurs in the same frame number in both cameras. (The speed of the dynamic event must be scaled appropriately with the image acquisition rate.)
- Measure the strobe or exposure signal from the cameras on an oscilloscope, if a strobe or exposure signal is output by the cameras.[a]

[a]These signals are typically only available on high-speed cameras, which are outside the scope of the current edition of this guide, and are not discussed further.

3.1.5 Application of the DIC Pattern

If using an applied DIC pattern (as opposed to the natural surface of the test piece), apply the selected DIC pattern to the test piece.

Recommendation 3.3 — Fiducials

Apply two fiducial marks a known distance apart on a portion of the test piece that is within the FOV, but outside the critical ROI. Assess the uncertainty in distance between the fiducials. These fiducials can be used to approximately verify the camera calibration, as described Sec. 3.3.2. Other fiducial marks can also be useful. For example, fiducial marks for the center line axis of a test piece or center of gauge section can be used to rotate the DIC measurement results to the test piece coordinate system, as described in Sec. 5.3.1.

Experience has shown that the use of certain inks, such as red ultra-fine-point permanent markers, to draw fiducial marks or lines before painting, can result in bleeding of the lines through the paint in such a way that they are visible, but do not overly degrade the pattern with respect to image correlation. Alternatively, dotted or dashed fiducial marks made on top of the pattern can still be readily detectable by manual inspection of the images, but will not degrade the pattern.

3.1.6 Pre-Calibration Review of System

Caution 3.4 — Pre-Calibration Review of System

This is the time to make adjustments and fix any issues with the DIC measurement setup, so that the best possible images are obtained. Once calibration images are taken, very few aspects of the DIC system can be changed without re-taking calibration images. If any adjustments are made to the optical system hardware (cameras or lenses), then the previously acquired images must be discarded and an entirely new set of calibration images must be acquired. Care and time at this point in the test procedure can save tremendous time later on.

3.1.6.1 Position Test Piece and Cameras

Place the test piece in load frame. Position the camera(s) to obtain the desired FOV, image ROI, and stereo-angle (for stereo-DIC). Set focus and aperture on the lens(es).

Tip 3.4 — Setting the Focus and Depth-of-Field

The test piece should be in the middle of the DOF and the focus should be constant across the ROI. To achieve these characteristics, first set the aperture wide open (low f-number). With the aperture open, the DOF is limited; thus it is easier to see when the test piece goes out of focus. To determine when the test piece is in focus, digitally zoom-in on the image and inspect the edges of DIC pattern features. Alternatively, some image acquisition software packages contain tools to automatically determine optimum focus. Adjust the focus ring of the lens to sweep through the DOF to find the bounds of the DOF. Once the bounds have been established, set the focus to be in the middle of the DOF bounds. Once the focus is set, decrease the aperture to have the desired DOF.

3.1.6.2 Verify Optical System

Verify FOV, focus, and DOF by translating the test piece within the region of the FOV in which it is expected to move and deform during the test.

3.1.6.3 Lock Adjustable Components

Adjust orientation of polarization filters if using cross-polarized light. Lock focal length (for a zoom lens), focus, and aperture rings if locks are included on the lenses. Strain relieve any loose or hanging cables.

3.1.6.4 Review Images

Review the image of the pattern using either a live image or an acquired static image. Look carefully for the following defects, which are illustrated in Fig. 3.2:

- Glare (e.g. glare from a glossy pattern, specular reflections, light reflecting from other objects directly into the lens)
- DIC pattern that is too sparse (i.e. fewer than 3 features (either dark or light) per intended subset size/element size), too coarse (i.e. features that are larger than 5 pixels), or too fine (i.e. features that are smaller than 3 pixels; see also Fig. 2.13 for an illustration of aliased features)
- Defects in applied pattern (e.g. scratches, smudges, foreign objects)
- Out-of-focus regions of the image
- Poor contrast
- Non-uniform lighting (either across the FOV, in time, or between two cameras in stereo-DIC)
- Overexposed or underexposed regions
- Dirt or foreign object on lens or camera detector (see Fig. 3.1)

- Vibrations or other camera motion (some of which can be detected by zooming in on a live image and looking for non-random motion)

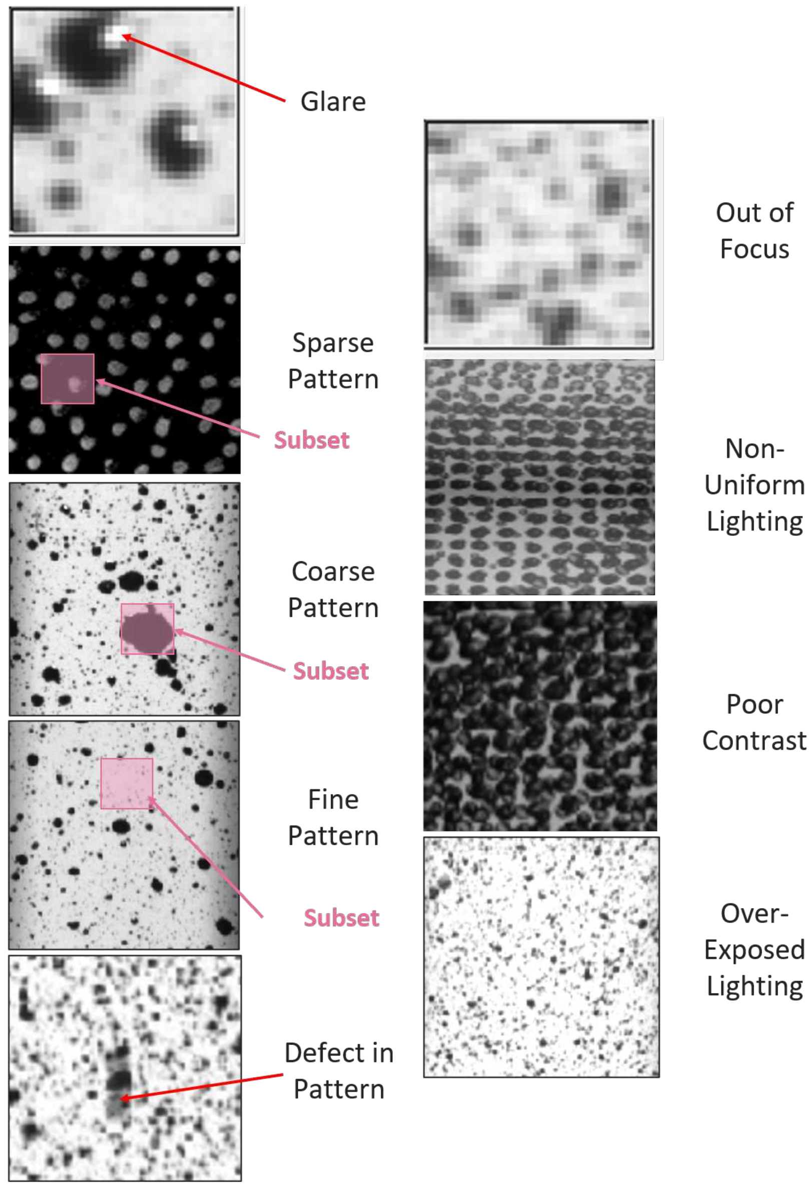


Figure 3.2: **Examples of several types of defects/issues with the DIC pattern or the DIC images that should be corrected before testing.**

Recommendation 3.4 — Review Images via Correlation Results

For a more thorough check of the DIC system, correlate static images of the test piece, as correlation results can often elucidate issues that are not obvious from visual inspection of the images. For 2D-

DIC measurements, check that sequential static images correlate. For stereo-DIC measurements, since at this point in time the stereo system has not yet been calibrated, use a 2D-DIC software to check that sequential images from each camera correlate.

If a certain region of the ROI in an image shows localized values of high correlation residual, look for the cause and remedy it before moving on. Some common sources of poor correlation results include (but are not limited to) the bulleted list above. As a diagnostic tool, the pattern may be translated and a couple more images may be acquired. If the region of poor correlation moves with the test piece, then the cause is likely something on the test piece (e.g. poor DIC pattern). If the region is at a fixed pixel location, then the cause is likely dirt or foreign object on the lens or camera detector (Sec. 3.1.2) or fixed light scatter reflections into a lens or camera (Sec. 2.2.4, Sec. 2.3.2.5).

Look for the presence of heat waves in the displacement fields. If significant heat waves are present, modify the test setup to minimize them. See Sec. 2.2.5 for more information.

3.1.6.5 Accept the DIC System

If the system is found to be acceptable, then proceed to calibration. If there are any unsatisfactory features in the images, including but not limited to the bulleted list in Sec. 3.1.6.4, adjust the DIC system to eliminate it. Then repeat this process iteratively as the system is modified, until satisfactory images are obtained.

Caution 3.5 — Accept the DIC System

Once satisfactory images are obtained, do not modify the system, and take care to not accidentally bump the camera(s), lens(es), or mounting system. Even the addition or removal of lens caps can subtly change the camera position or lens focus.

3.2 Calibration

3.2.1 Purpose of Calibration

The goal of calibration of a 2D-DIC system is to establish the image scale, i.e. the number of pixels in the image that corresponds to a certain physical distance on the test piece, and to correct for lens distortions.[16] The goal of stereo-DIC calibration is to determine both the intrinsic camera parameters (i.e. image scale, focal length, image center, lens distortions, etc.) as well as the extrinsic parameters of the stereo-DIC system (i.e. stereo-angle, distance between cameras, distance from cameras to object, etc.).[17]

Caution 3.6 — Calibration of 2D System

If strains are the primary QOI, then calibration of a 2D system is often overlooked and considered unnecessary, since strain is a unitless quantity, and an image scale is not required to calculate strain.

[16] If the intrinsic and extrinsic parameters of a 2D, single camera system are calibrated, then an out-of-plane tilt of the test piece can be determined and corrected [4]. However, this is an advanced topic that is outside the scope of the current edition of this guide.

[17] Typically, both intrinsic and extrinsic parameters are calibrated simultaneously in a stereo-DIC system. However, some software allows for calibration of the intrinsic parameters of each camera-lens pair, and calibration of the extrinsic parameters of the stereo-system separately. However, this process is outside the scope of the current edition of this guide.

However, neglecting to correct lens distortions may add error to the measured displacements and result in additional error in the calculated strains [1, Sec. 3.1.2], [41].

Recommendation 3.5 — Calibration of 2D System

When using 2D-DIC, assess the magnitude of lens distortions for a given optical system, by acquiring and correlating images of a DIC pattern as it is translated in-plane across the FOV. It is important that the translation remain strictly perpendicular to the optical axis; otherwise, false strains due to out-of-plane motion will be convolved with lens distortions. If errors from lens distortions are negligible (i.e. insignificant compared to the overall noise-floor (Sec. 5.4.2)), then 2D calibration can be omitted. If errors from lens distortions are significant, however, calibration is strongly recommended, to determine the intrinsic camera parameters and correct lens distortions.

If full calibration of a 2D-DIC system to correct lens distortions is omitted, a simplified calibration to establish the image scale is still recommended. An approximate image scale can be computed by dividing the camera resolution by the FOV. Alternatively, the image scale can be calculated from images of a resolution target. It is recommended to verify the image scale in both the vertical and horizontal directions.

3.2.2 General Calibration Steps

Caution 3.7 — Pre-Calibration Review

Before beginning the calibration process, be sure that all steps in the pre-calibration review of the DIC system (Sec. 3.1.6) have been completed.

3.2.2.1 Select Calibration Target

Select a calibration target of an appropriate size. Consult the manual of the DIC software for recommendations regarding the selection of an appropriate calibration target.

Recommendation 3.6 — Selection of Calibration Target

Ideally, the calibration target should be approximately the same size as the FOV, or slightly smaller. If no calibration target is available that is approximately the same size as the FOV, then two other options are possible. A first option is to print the correctly sized target on computer paper using a standard office printer, and glue or tape the paper calibration target to a rigid plate. In this case, the feature spacing should be accurate to within 0.1 pixels [42]. A second option is to use a smaller target; however, the target should not be smaller than approximately one half of the FOV.[a] In this case, ensure that the features on the calibration target are still large enough to be resolved by the imaging system and extracted by the DIC software. Also, additional calibration images will be required in order to have a sufficient number of well-extracted features in the entire working volume of the optical system, which is discussed in Sec. 3.2.2.4.

[a]Targets smaller than one half of the FOV may produce acceptable calibrations, but extra precautions are required, which are beyond the scope of the current edition of this guide.

Recommendation 3.7 — Metrologically Traceable Calibration Target

Scaling of DIC coordinates and displacements from pixels to physical units (e.g. millimeters) is completely dependent on accurate and precise measurements of the feature spacing on the calibration target. If the physical units are a critical aspect of the measurements to be made, it is recommended to use calibration targets that have been independently measured and are metrologically traceable to the International System of Units (SI).

3.2.2.2 Clear Working Space

Create a clear working space in which the calibration will be performed, so that the selected calibration target can be held, rotated, tilted, and translated as needed (requirements will be different for 2D-DIC and stereo-DIC calibration) at approximately the same SOD as the test piece.

Recommendation 3.8 — Clear Working Space

There are two strategies for creating a clear working space:

1. Remove the test piece from the load frame and move the grips back (if necessary).
2. Move the DIC system. If moving the DIC system is necessary, then the following are recommended:
    - Move the system along only a single degree of freedom, such as translating the rig backwards away from the load frame, or rotating the bar on which the two cameras are mounted. Moving the system along two or more degrees of freedom (e.g. rotating and translating, or translating along two directions) is also permissible, but not preferred.
    - If possible, calibrate the cameras in the same orientation (i.e. horizontal or vertical) as they will be mounted during the test. If the orientation is changed between the calibration and the test, the optics inside the lens may shift slightly, changing the focus, aperture, zoom etc.

Caution 3.8 — Relative Motion between Cameras

If the DIC system is moved, it is imperative that the two stereo cameras are moved only as a rigid pair, and that there is no relative motion between the two cameras. Ensure that the two cameras are locked rigidly together during any adjustment of the position of the stereo rig. Any relative motion between the two cameras — even small changes on the micrometer scale — during calibration, or when repositioning the cameras after calibration, will result in errors in the DIC measurements.

Recommendation 3.9 — Verification of Calibration

Verification of the calibration (see Sec. 3.3.2) is strongly recommended after returning the test piece and/or stereo system to the position to be used for measurements, to ensure that no relative motion occurred between the two cameras during the repositioning of the test piece and/or stereo system.

3.2.2.3 Adjust Lighting

Ensure the contrast is sufficiently large and uniform across the entire calibration target, and that there is no glare for all desired positions and orientations of the target. These conditions should be true for both cameras for stereo-DIC. Adjust lighting and/or exposure time if necessary.

Tip 3.5 — Lighting for Calibration

The lighting and exposure for the actual DIC measurement images of the DIC pattern and for the calibration target are completely independent. For example, some calibration targets require back-lighting, which necessarily requires different lighting than that used for the images of the test piece during the mechanical test. Also, the lighting and/or exposure may need to be adjusted for different positions/orientations of the calibration target. Additionally, cross-polarized light may be used to eliminate glare from the target.

Caution 3.9 — Lighting for Calibration

Any changes in lighting should not disturb the cameras or their mounting. Refer to Sec. 2.2.4.2 for recommendations on mounting lights.

Caution 3.10 — Equipment Adjustments after Calibration

While lighting and exposure may be adjusted, aperture and focus may not be adjusted between calibration images of the calibration target and DIC measurement images of the DIC pattern. Additionally, the light wavelength should remain the same for both calibration and DIC measurement images.

3.2.2.4 Acquire Calibration Images

Acquire calibration images such that there are well-extracted features in the entire volume to calibrate (Fig. 3.3). This "calibration volume" is typically a subset of the total working volume of the stereo system (Fig. 1.1).[18]

[18] The Stereo-DIC Challenge, conducted under the auspices of the Society of Experimental Mechanics, is currently underway. Among other things, the Challenge seeks to explore the effects of the location and orientation of the calibration target, number of calibration images, etc. Recommendations for calibration based on this challenge may be included in a future edition of this guide.

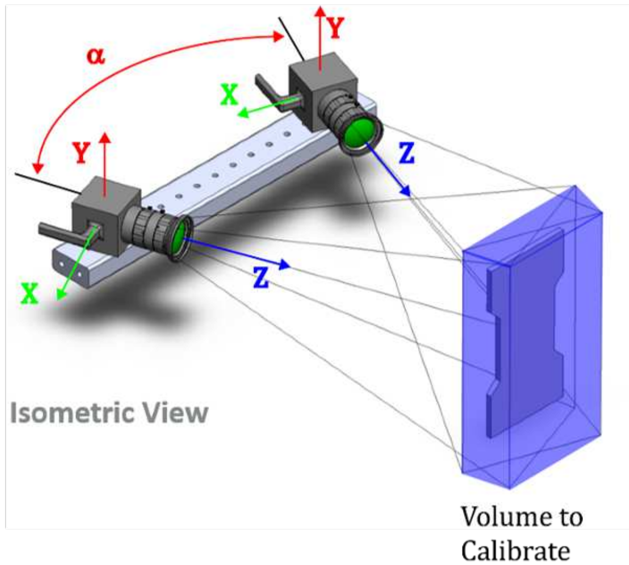


Figure 3.3: Schematic illustrating the volume to calibrate, in which calibration images should be acquired.

Recommendation 3.10 — Calibration Target Positions and Orientations

While there are slight variations for different software packages, typically the following positions and orientations of the calibration target are recommended for stereo-DIC calibration (Fig. 3.4):

1. Rotate about the vertical image axis.
2. Rotate about the horizontal image axis.
3. Rotate about the optical axis.
4. Plunge towards and away from each camera, along its optical axis.
5. If the calibration target is smaller than the FOV, translate horizontally and vertically, so that features from the calibration target fill the entire FOV of each camera.
6. Rotate 90 degrees about the optical axis and repeat the above steps.[a]
7. Perform combinations of the above positions and orientations (i.e. rotate about the horizontal and vertical axes simultaneously while plunging along the optical axis).

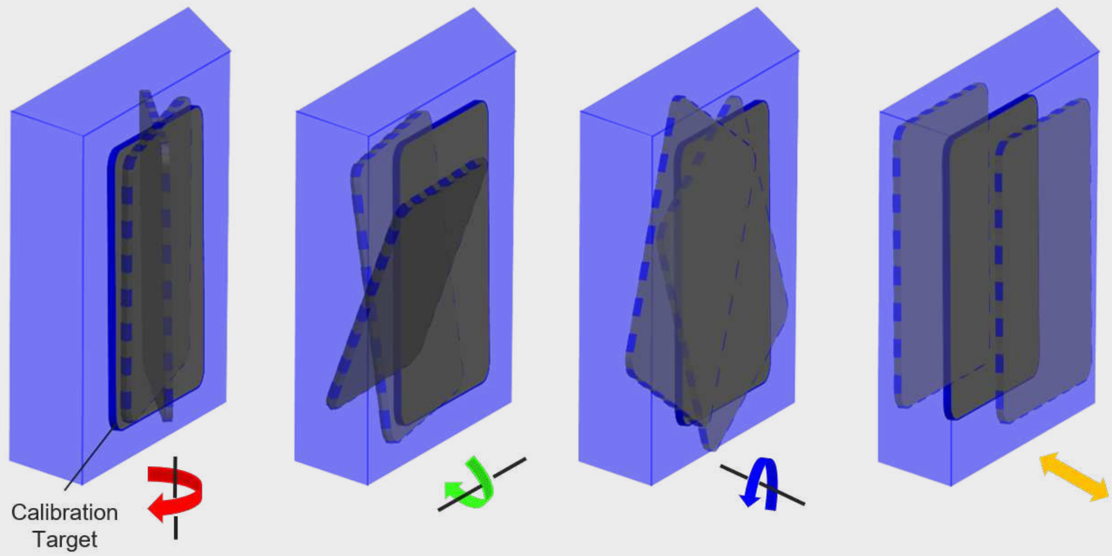


Figure 3.4: Schematic illustrating the recommended positions and orientations of the calibration target, including rotating about the three axes and plunging along the optical axis.

[a]Manufacturing techniques of calibration targets vary, but some methods may result in a unidirectional stretch of the pattern on the calibration target. That is, features may have a slightly different spacing along the horizontal axis compared to the vertical axis. While using targets that have been independently measured is recommended (see Sec. 3.2.2.1), rotating 90 degrees about the optical axis is an additional precaution to help to compensate for any unidirectional stretch of the pattern on the calibration target.

Tip 3.6 — Number of Calibration Images

The number of calibration images required or recommended depends on the calibration target and DIC software, ranging from as few as 8 images up to 50–100 images. Three-dimensional calibration targets (targets that have features on two different planes) may require fewer images than two-dimensional calibration targets (targets that have features on only a single plane). Consult the user manual of the software for software-specific procedures.

Recommendation 3.11 — Holder for Calibration Target

Ideally, a rigid calibration target holder is recommended to ensure that the calibration target is stationary when images are acquired. The rigid holder can be mounted on translation and rotation stages or on an adjustable and lockable ball-in-socket joint, to allow displacement and rotation of the target between images.

In cases where using a rigid calibration holder is not practical, holding calibration targets by hand is often also acceptable. If the calibration target is held by hand, hands should be braced against something rigid, and the exposure time should be limited to approximately 25 ms or less, to reduce motion blur. Holding calibration targets by hand is not recommended for FOVs smaller than approximately 50 mm, since even small motions of the target can result in blurry images.

Caution 3.11 — High-Quality Calibration Images

It is more important to have high-quality images (i.e. in focus, good contrast, no glare, filling the entire calibration volume, etc.) than to have a large number of images. Take care to keep the calibration target within the calibration volume, so that the calibration target remains in focus, and ensure there is good contrast and no glare on the calibration images.

Recommendation

Some software packages show a live evaluation of the quality of the extraction of calibration target features, and will only acquire an image if the features are extracted well. Other software packages extract features only after all calibration images have been acquired. If using software that follows the second methodology, a surplus of images can be acquired, allowing for some images and/or features to be excluded due to poor quality. Be careful, though, not to exclude all images from a certain region of the calibration volume.

Caution 3.12 — Calibration Score

For stereo-DIC, the calibration procedure is a minimization process that seeks to find the best set of intrinsic and extrinsic parameters, given a set of extracted calibration features. Different software packages have different metrics or "scores" for the final parameter values obtained by the minimization. Often, it is possible to have a better score with fewer images, or with a smaller volume filled by features from the calibration target. This scenario is analogous to obtaining a higher coefficient of determination (R^2 value) of a polynomial fit of a set of data points when fewer points are used. However, if a reduced number of data points is used in the minimization process, the final parameter values may not represent the optical system with high fidelity [42].

Recommendation

Take a sufficient number of images to have features that fill the calibration volume, even if the calibration "score" is worse with more images covering a larger volume, compared to the score with fewer images covering a smaller volume.

3.2.2.5 Calibrate System

Select an appropriate camera or lens-distortion model,[19] and calibrate the system with the DIC software of choice. Refer to the manual of the software for details on the calibration process.

3.2.2.6 Review Calibration Results

Review the calibration results.

[19] Selection of the camera and lens-distortion model is an advanced topic and is both hardware- and software-specific; therefore, no further information is given in the current edition of this guide. Consult the DIC vendor for more information on selection of the appropriate settings for the software and hardware.

Tip 3.7 — Review of Calibration Results

This review is dependent on the software utilized; consult the user manual for specific suggestions for the DIC software. Some possible aspects of the calibration results to review (if the software provides access to these aspects) include:

- Check the images or features that were rejected and see if there was an obvious reason for rejection. This is particularly instructive for new users and/or experienced users working with new hardware setups. It can improve a user's ability to produce better quality calibration images in the future by learning what not to do (i.e. the user can see the effects of poor lighting or reflections, poor finger or holder placement that blocks key features of the target, defocused images, etc.).
- Verify that the remaining accepted images still fill the calibration volume. (That is, make sure the rejected images were not all from the same region of the volume or from the same angle of the calibration target.)
- Verify that the features extracted from the accepted images are correct. (For example, sometimes the software will extract a feature that is actually dirt or glare on the calibration target.)
- Compare the calibration score from individual images to the score of the final calibration. Also compare the calibration score for a given image from each camera if using stereo-DIC. Consider removing images manually whose individual score is significantly higher than the overall score, or significantly different between the two cameras. Alternatively, consider removing individual extracted features so that the individual score of the image is on par with the overall score.
- If possible, save a copy of the individual image calibration scores, in addition to the overall score and calibration results. This information can be useful in diagnosing problems later in the analysis, or problems with one camera and lens versus another.
- Some DIC software packages will alert the user to possible synchronization errors after the calibration procedure is complete. Synchronization errors typically only occur if the user is using a hand-held calibration target whose motion is not completely stopped when images are acquired, or if vibrations are causing significant camera motion when images are acquired. As a diagnostic tool, if a synchronization error or camera vibrations are suspected, one can try to calibrate the intrinsic parameters for each camera individually. If each camera can be calibrated individually with an acceptable calibration score, but the extrinsic parameters of the stereo-system cannot be calibrated, or if the calibration score of the stereo system is unacceptable compared to the scores of the individual camera calibrations, then a synchronization error, or camera vibrations, are likely.

Tip 3.8 — User-Defined Inputs for Calibration

The amount of control the user has, and the number of user-defined inputs in the calibration procedure, varies with different DIC software packages. For example, some software allows the user to select the threshold for extracting features from the calibration target, or to define the lens distortion model that is used; other software is a black box (i.e. closed system) with calibration images as inputs, and a calibrated camera model and calibration score as outputs. If the DIC software has any user-defined settings, explore the effect of these settings on the calibration results.

3.2.2.7 Review Calibration Parameters

Compare the values of the calibration parameters to their corresponding physical values [43].[20]

Recommendation 3.12 — Review of Calibration Parameters

Typical parameters to check include (Fig. 3.5):

- **Image center:** For most camera detector and fixed-focal length lens combinations, the intersection of the optical axis with the detector should be near the center of the detector array (e.g. if using a 5 MP camera that is 2448 x 2048 pixels, the calibrated image center should be close to (1224,1024)). This should be true for both cameras of the stereo pair, if the same type of camera and lens are used. Small variations from the detector center are to be expected, but non-physical values (e.g. negative values) or extreme values (e.g. near the detector edge) should be investigated and corrected when possible. When using a zoom lens, however, it is common for the optical axis to be far from the image center, due to the complexity of the optics inside of a zoom lens.

- **Lens focal length:** The calibrated focal length of the lens, in physical units, can be compared to the reported focal length of the physical lens. Note that the physical lens focal length reported by the lens manufacturer may be only an approximate value of the actual lens focal length (e.g. a lens manufacturer may call a certain lens a 50 mm lens, when in reality the focal length is 47.5 mm). If the calibrated focal length of the lens is reported in pixels, it can be converted to physical units by multiplying by the camera detector pixel size in physical units.

- **Skew:** Skew represents a deviation from the right angle (90°) between the two axes of the camera detector. For modern detector manufacturing methods, the skew should be negligible. However, due to the covariance of the camera model parameters, especially for complex imaging setups, the skew parameter may be non-zero.

- **Angles:** The reported stereo-angle should be approximately the same as the physical angle between the two cameras (if using stereo-DIC) . The other two angles should be approximately zero if the stereo-plane is perpendicular to the test piece, as described in Sec. 2.2.2 for standard orientation of the stereo system.

- **Distance between two cameras:** The reported straight line distance between the two cameras should be approximately the same as the distance between the two camera detectors (if using stereo-DIC).

[20] Individual parameters can be completely wrong vis-à-vis their corresponding physical values, yet together, the calibration parameters give an accurate triangulation, and accurate displacement results. Therefore, nonphysical parameters are not necessarily problematic [42]. However, this scenario typically only arises in complicated DIC measurement setups, and thus is outside of the scope of the current edition of this guide, which covers only standard laboratory conditions.

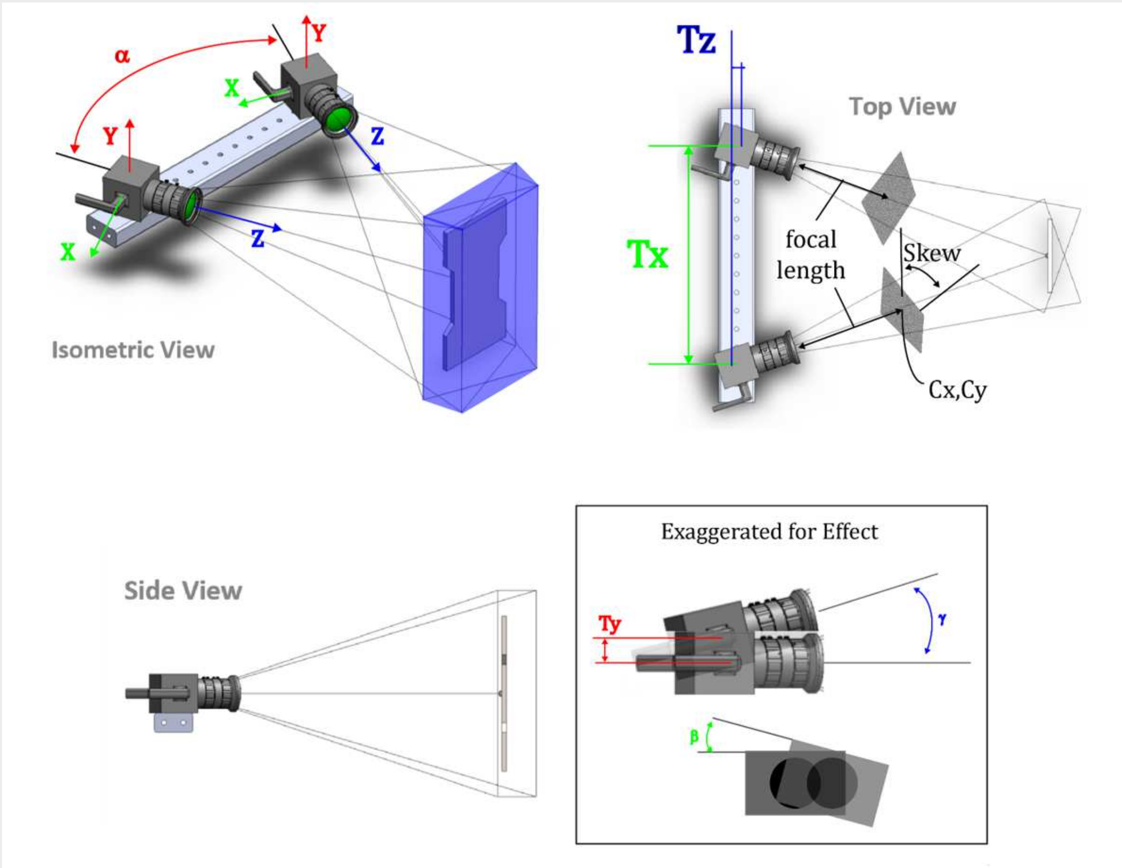


Figure 3.5: **Schematic illustrating several typical calibration parameters, including intrinsic parameters such as the image center (C_x and C_y), lens focal length, and detector skew, and the extrinsic parameters of three rotations and translations that describe the relative position of the two cameras (α, β, γ, T_x, T_y, and T_z).**

Tip 3.9 — Review of Calibration Parameters

Because the physical values are often hard to measure precisely, this review is a very broad assessment, to make sure the calibration parameters are in the correct range of values, rather than a very precise comparison between the calibration parameters and corresponding physical values. Additionally, tracking of these values for systems that are not changed/adjusted between calibrations can lead to user experience, and tighter ranges on what is considered acceptable.

Caution 3.13 — Calibration Score

The calibration score reported by the software can in some cases be misleading. Refer to Caution 3.12 in Sec. 3.2.2.4 for more details.

3.3 Post-Calibration Routine

The post-calibration routine described in this section has three purposes: to verify the calibration of the optical system, to acquire images for the noise-floor analysis (Sec. 5.4.2), and to perform a final review of the DIC system before conducting the mechanical test with DIC measurements.

3.3.1 Images for Calibration Verification and Noise-Floor Analysis

3.3.1.1 Reset System

Replace the test piece if it was removed to take calibration images. If the stereo system was moved to take calibration images, replace it to its normal position to view the test piece, and be sure to lock any moving components on the mounting system.

3.3.1.2 Adjust Lighting

If the lighting and/or exposure were adjusted for the calibration images, readjust lighting and/or exposure for the DIC pattern on the test piece.

3.3.1.3 Acquire Static Images

Acquire static images of the test piece.

Recommendation 3.13 — Static Images for Measurement Uncertainty Quantification

Ideally, the static images should be acquired at the same frame rate as that used for the test, and for the same duration of the test, in order to capture representative sources of noise or error. For example, high-frequency vibrations may not be represented if images are acquired at a slow frame rate. Alternatively, low-frequency errors, such as heat waves or camera drift, may not be represented if images are acquired over a short duration. Also, for some cameras, camera noise is a function of frame rate.

Acquiring static images at the same frame rate and for the same duration as the test, however, doubles the amount of data that must be stored and processed, which can be non-trivial for many DIC measurements, in which gigabytes of images and processed data are accumulated. Therefore, the number and timing of static images is often a compromise between representing the noise sources present in the DIC measurement, and practical considerations of data size.

One possible strategy to minimize the number of images required for the noise-floor, while still representing all noise sources, is to acquire a burst of images at the desired frame rate at the beginning and the end of the test duration time. In this way, both high-frequency and low-frequency error sources are captured in the static images.

3.3.1.4 Review Images

Perform a final review of the images from Sec. 3.3.1.3 as described in Sec. 3.1.6.4 and address any issues that are found.

Caution 3.14 — Recalibration of the System

If adjustments are made to the camera(s) or lens(es), the calibration process will have to be repeated. However, making adjustments to achieve the best-possible images is usually preferable to producing poor quality or even useless DIC measurements just to avoid recalibrating the system.

3.3.1.5 Acquire Rigid-Body-Motion Images

Rigidly translate and rotate the test piece and acquire additional images.

Tip 3.10 — Rigid-Body-Motion Images

The applied translations/rotations can either be applied by hand where the exact applied displacements are unknown, or with translation/rotation stages with micrometers, such that the applied displacements are known within the uncertainty of the stage.

Recommendation 3.14 — Rigid-Body-Motion Images for Stereo DIC

At a minimum, translate the test piece within the volume in which it is expected to move during the test. For a more thorough review of the calibration, acquire additional images that cover the entire FOV and DOF of each camera.

Recommendation 3.15 — Rigid-Body-Motion Images for 2D DIC

For 2D-DIC, capture both in-plane translations and out-of-plane translations and rotations. The two groups of images — in-plane translations versus out-of-plane motions — should be kept separate, so that the effects of in-plane versus out-of-plane motion can be analyzed independently. The in-plane images will be used to verify adequate correction of lens distortions (Sec. 3.3.2.1) and to calculate the noise-floor of QOIs. The out-of-plane motions will be used to estimate the bias errors caused by out-of-plane motion during the mechanical test (Sec. 5.4.3).

3.3.2 Verification of Calibration

Correlate the static and rigid translation images, and verify the calibration results using the methods described in this section. If the calibration is determined to be unsatisfactory based on any of the following metrics, improve the calibration before continuing. Otherwise, accept the calibration, and proceed to a post-calibration review of the system (Sec. 3.3.3).

Tip 3.11 — Improving the Calibration

Improvement may require adjusting software-specific parameters in the calibration procedure, taking additional calibration images, or adjusting the optical system hardware (cameras or lenses).

Caution 3.15 — Adjusting Optical System Hardware during Calibration

If any adjustments are made to the optical system hardware (camera(s) or lens(es)), then the previously acquired calibration images must be discarded, an entirely new set of calibration images must be acquired, and the calibration process must be redone.

Tip 3.12 — User-Defined Parameters for Calibration Verification

The final DIC user-defined parameters (e.g. subset size, step size, virtual strain gauge size for local DIC, or element size and element shape function for global DIC (Sec. 5.2)) will not be selected until after the actual mechanical test has been conducted and a noise-floor analysis has been completed (Sec. 5.4). Therefore, at this point, use default settings provided by the software, or expert judgment and past experience, to select reasonable parameters for the correlation of the static and translation images for purposes of verifying the calibration and performing a final review of the DIC system.

3.3.2.1 Intrinsic parameters

The primary purpose for verifying intrinsic parameters is to verify that lens distortions are properly corrected. Correlate the translation images acquired in Sec. 3.3.1 and remove rigid-body motion. Lens distortions will manifest as an elliptical shape in the displacement or strain contour plots, as shown in Fig. 3.6.

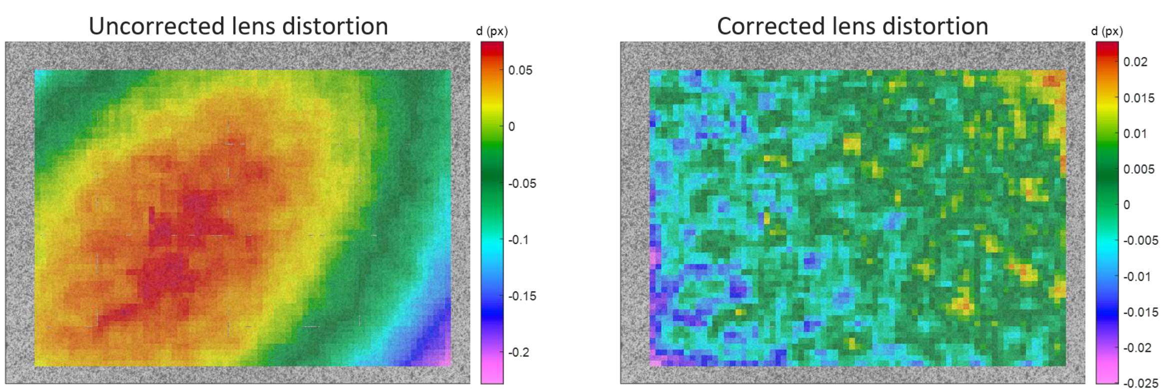


Figure 3.6: The displacement magnitude (after rigid-body-motion has been removed) when lens distortions are not corrected (left) or properly corrected (right).

Recommendation 3.16 — Evaluation of Lens Distortions

Evaluation of lens distortions is subjective. Compare the magnitude of the errors from lens distortions to the total noise-floor of the displacements and strains (see Sec. 5.4.2). If errors from lens distortions are significant compared to the noise-floor, adjust the type and/or magnitude of the distortion correction in the calibration procedure. If distortions cannot be removed through the correction process in the calibration procedure, then either a custom correction procedure will need to be implemented, the choice of optical system (lens and camera) should be revisited, and/or the image ROI will have to be limited in size and motion to only the portion of the FOV with an acceptable level of distortion.

Caution 3.16 — Evaluating Lens Distortions for 2D-DIC

For 2D-DIC, it is important that the translation images are strictly perpendicular to the optical axis. Otherwise, false strains due to out-of-plane motion will be convolved with lens distortions, and the translation images cannot be used to verify lens distortions alone.

3.3.2.2 Extrinsic parameters

Extrinsic parameters are applicable only for stereo-DIC, and are not applicable for 2D-DIC. The primary metric for verifying the extrinsic parameters is the epipolar error. Depending on the DIC software, the epipolar error may be called by a different name, such as projection error, three-dimensional residuum, intersection error, or correlation deviation. There are slight differences in how these metrics are calculated in different software packages, but the basic principle is universal. To verify the extrinsic parameters, correlate the static images (and translation images if available) acquired in Sec. 3.3.1 and verify that the epipolar error is acceptable based on the DIC software documentation.[21,22]

Tip 3.13 — Acceptable Level of Epipolar Error

There is not a single, fixed threshold for the epipolar error that separates "good" from "bad" calibrations. Rather, there is a direct relationship between epipolar errors and errors in DIC measurements, with larger epipolar errors resulting in larger errors in DIC measurements. As a rule of thumb, though, the epipolar error should typically be on the order of the calibration score; if the epipolar error is significantly larger than the calibration score, the cause of the large error should be investigated and rectified.

Tip 3.14 — Spatially-Resolved Epipolar Error

Some DIC software packages only report the average epipolar error over the image ROI, while others report the epipolar error for each subset. If the DIC software reports spatially-resolved epipolar error, then the epipolar error can additionally be used to evaluate the DIC pattern and lighting, similar to using the correlation residual in the first preliminary correlation as described in Sec. 3.1.6.4.

Tip 3.15 — Lens Distortions and Epipolar Error

Uncorrected lens distortions, in addition to the extrinsic parameters, will also influence the epipolar error. However, if the lens distortions are properly corrected and intrinsic calibration parameters are verified as described in Sec. 3.3.2.1, then the epipolar error is primarily related to the extrinsic

[21] See footnote *b* on page 20 for a note concerning correction of extrinsic parameters of a camera calibration.

[22] If images of the calibration target were of a different image size than the static and rigid translation images of a DIC pattern, then the calibration images must be adjusted for cropping; failure to do so will result in an inflated value of the epipolar error. However, discussion of image cropping is beyond the scope of the current edition of this guide.

calibration parameters.

Local-Global Flag 3.1 — Calibration Verification

See Appendix C.3.2.2 for information on reviewing and verifying the calibration for global DIC.

3.3.2.3 Absolute distances

Verify that the DIC measurements are reporting accurate values for absolute distances.

Recommendation 3.17 — Verification of Absolute Distances

Some suggested metrics include, but are not limited to:

- **Fiducial Marks:** If fiducial marks of a known distance were placed on the test piece as recommended in Sec. 3.1.5, compare the distance between the fiducial marks calculated by the DIC software in the correlation of the static images or the translation images to the known distance. This is only an approximate assessment, since the calculated distance from the triangulation is known only to within +/- 1 pixel at best, due to manual selection of the center of the fiducial marks, and there is some uncertainty in the known distance as well. However, it is a good sanity check to ensure that the correct target size was entered into (or identified by) the DIC calibration software.
- **Applied Displacements:** If the applied displacements are known for the rigid translation images, compare the DIC results to the applied displacements. This is typically only an approximate assessment, as precision on DIC results is typically higher than precision of the "known" displacements if a standard micrometer translation stage is used.

3.3.3 Post-Calibration Review of System

Perform a final review of the DIC system. If any aspect of the DIC system is determined to be unsatisfactory based on the final review of the system, adjust the system and review it again.

Caution 3.17 — Adjusting Optical System Hardware during Calibration

If any adjustments are made to the optical system hardware (camera(s) or lens(es)), then the previously acquired calibration images must be discarded, an entirely new set of calibration images must be acquired, and the calibration process must be redone.

3.3.3.1 Noise-Floor

Perform an abbreviated noise-floor analysis and verify that the noise-floors of the QOIs are acceptable.

Recommendation 3.18 — Abbreviated Noise-Floor Analysis

A full noise-floor analysis, as described in Sec. 5.4.2, can be time consuming, and also requires *a priori* knowledge of the test piece deformation, in order to select DIC user-defined parameters (e.g. subset size, step size, virtual strain gauge size for local DIC, or element size and element shape function for global DIC (Sec. 5.2)). Therefore, at this point in time, before the mechanical test has been conducted, an abbreviated noise-floor analysis is recommended.

Compute the spatial standard deviation of the QOIs from the static images acquired previously (Sec. 3.3.1.3) using estimated DIC user-defined parameters based on vendor defaults, past experience, or expert judgment. If the static images were acquired at the desired frame rate of the actual test, also compute the temporal standard deviation. Verify that the standard deviations (i.e. the noise-floor) are acceptable (Sec. 2.1.9).

3.3.3.2 Heat Waves

Look for the presence of heat waves in the displacement contour plots from the static images. If significant heat waves are present, modify the DIC measurement and/or mechanical test setup to minimize them. See Sec. 2.2.5 for more information.

3.3.3.3 Stability

If a significant amount of time passes between calibrating the DIC system and performing the mechanical test with DIC measurements, consider retaking static images and rechecking the camera calibration. Any increase in the epipolar error or noise-floor should be investigated and rectified.

3.3.3.4 Other Verifications

In addition to the guidelines outlined here, individual users or laboratories may have additional in-house procedures that include details specific to the mechanical test setups, equipment, and software that are commonly used in each laboratory. As a matter of good practice, it is recommended that in-house procedures be documented and that criteria be established to determine if a specific calibration and/or noise-floor (Sec. 5.4.2) is acceptable for the intended purpose of the DIC measurement. This will help prevent wasting time and resources to complete DIC measurements during a mechanical test, only to realize after the fact that the images are unsatisfactory.

4 — Execution of the Test with DIC Measurements

Once all details of the DIC measurement setup and mechanical test setup have been finalized, and the cameras have been calibrated, the actual mechanical test can be conducted, with concurrent imaging for DIC measurements. Before conducting the test, review all data acquisition systems, such as:

- The correct file name, location, and storage capacity for DIC images has been set.
- The correct test procedure or macro has been selected.
- Force signals and other measurement signals from the load frame are set to record and are synchronized with DIC images.
- Triggering of the load frame and/or DIC images is ready.

> **Caution 4.1 — Static Reference Image**
>
> Ensure at least one image is acquired of the test piece prior to any applied force or displacement.

- Lights are turned on, exposure is correct, and frame rate is correct.

As this guide does not cover the mechanical test itself, no further guidelines are provided here for the actual execution of the test.

5 — Processing of DIC Images

5.1 DIC Software

Once the mechanical test has been performed and DIC images have been acquired, the images are processed using DIC software. There are both commercial (typically closed-source) DIC packages as well as independently developed (often open-source) software. The choice of software depends completely on the user, and the user is directed to the software manual for specific details on how to use the software.

As part of the DIC Challenge [44, 45], a set of images to verify DIC software has been carefully designed and vetted. These images are available at `https://idics.org/challenge`. Users of closed-source DIC software can use these images to explore the "black box" (closed system) of the DIC software. Additionally, users of independently developed DIC codes are strongly encouraged to verify their codes using these images, and to document the results of the verification.

5.2 User-Defined Correlation Parameters

There are many user-defined parameters in the DIC analysis procedure that must be selected. Here, some general comments are made, but detailed training — either on-the-job training by more experienced DIC practitioners, training by a vendor when a new DIC system is purchased, or classes taught by subject-matter experts[23] — is strongly recommended. Additionally, the user should refer to the manual for the DIC software of choice for more details that are specific to the software.

5.2.1 Reference Image

DIC tracks the motion, in a Lagrangian sense, of a set of interrogation points defined on a reference image. There are three approaches for selecting a reference image:

1. **Single reference image:** The simplest and preferred approach for selecting a reference image is to use an image at the beginning of the series, of an undeformed test piece, prior to the application of any displacement or force. Motion or displacement of the interrogation points is then tracked over time by correlation of subsequent images in the series back to the initial reference image.

> **Caution 5.1 — Static Reference Image**
>
> It is critical that the reference was acquired prior to any applied displacement or force.

[23] iDICs offers DIC classes at their annual conference. For more information, see `www.idics.org`.

Otherwise, all DIC measurements correlated with respect to the reference image will be biased by an unknown amount.

Tip 5.1 — Noise-Free Reference Image

One can acquire several (approximately 30) images of the stationary, undeformed test piece and average these images together. This averaged reference image can then be used as an approximately noise-free reference image [46].

Tip 5.2 — Reference Image for Stereo-DIC

In stereo-DIC, typically a single image from one of the cameras is selected as the primary reference image. User-defined correlation parameters such as the ROI of the image and the subset size are defined on this single image. Next, the correlation can proceed one of two ways depending on the software, as illustrated in Fig. 5.1. In the first option, the matching criterion, along with the parameters of the stereo-system calibration, are used to match subsets from the primary reference image in the first camera to the corresponding dependent reference image from the second camera. Then, succeeding images in the first camera series are compared back to the primary reference image of the first camera; in parallel, succeeding images of the second camera series are compared back to the dependent reference image of the second camera. In a second option, all images from both camera series are compared back to the primary reference image of the first camera.

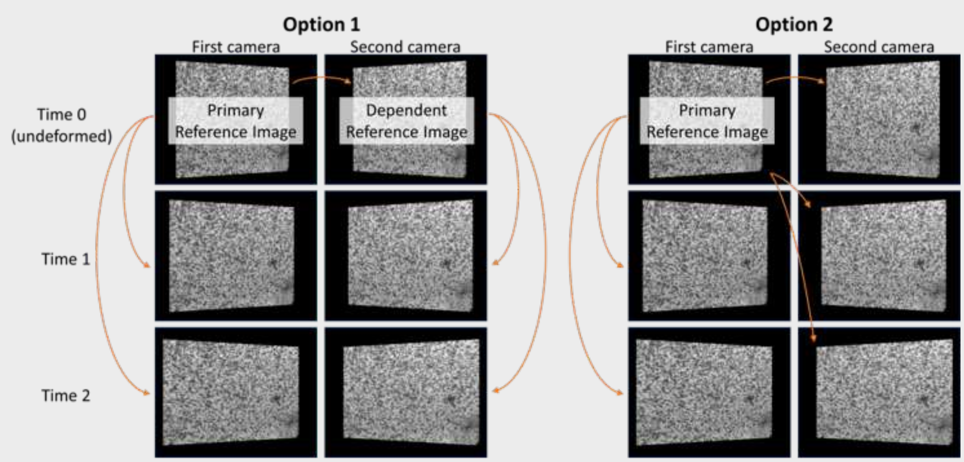


Figure 5.1: Schematic illustrating two different approaches to reference images and the correlation process for stereo-DIC.

2. **Incremental correlation:** In some cases, the DIC pattern may change significantly during the course of the test, such that the DIC pattern of the deformed test piece cannot be correlated back to the initial reference image of the undeformed test piece. In this situation, incremental correlation may be used, where each image is correlated to the previous image, rather than to the same, initial reference image of the undeformed test piece. Incremental correlation gives incremental displacements between each of the images; total displacements from the initial reference image

of the undeformed test piece are computed by summation of the incremental displacements. The drawback to incremental correlation, though, is that errors in the total displacements are also summed, and thus errors typically increase with increasing number of images in the incremental correlation sequence.

3. **Partitioned correlation:** As a compromise between using a single reference image of the undeformed test piece and incremental correlation, the series of images may be partitioned into sub-series, and the images in each sub-series are correlated back to the image at the beginning of that sub-series. For example, let image 1 be the primary reference image of the undeformed test piece. Then, images 2-100 may be correlated back to image 1; images 101-200 may be correlated back to image 100; images 201-300 may be correlated back to image 200; etc. The total displacement of image 300, relative to image 1 of the undeformed test piece, is then given by the displacement of image 300 relative to image 200 plus the displacement of image 200 relative to image 100 plus the displacement of image 100 relative to image 1. By updating the reference image periodically instead of using the previous image, accumulation of errors is reduced.

5.2.2 Pre-Filtering of Images

Subset interpolants often perform better with smooth spatial gradients in image intensity. For this reason, applying a digital low-pass filter (e.g. a Gaussian filter) to the images prior to correlating them, to reduce high-frequency content by reducing random image noise and softening the edges of a particularly sharp DIC pattern, can be beneficial [47, 48].

Tip 5.3 — Low-Pass Image Pre-Filters

Low-pass filters are also known to mitigate the effects of under-resolved DIC pattern features (i.e. smaller than 3 pixels) in many cases. Note, though, that physical anti-aliasing filters (see Tip 2.11) and digital low-pass filters are fundamentally different. The first prevents aliasing in the analog realm, so that no aliased information is encoded in the images. The second attempts to mitigate the effects of aliasing in the digital realm, after aliased information has been encoded in the images. See [38] for more details.

Caution 5.2 — Low-Pass Image Pre-Filters

Low-pass filtering can also have detrimental effects in some cases (e.g. low-pass filtering can bias the results) [47, 48]. Therefore, DIC practitioners should be judicious in the use of digital filters.[a]

[a]More specific guidelines regarding digital pre-filtering of images may be included in a future edition of this guide.

Recommendation 5.1 — ~~Physical Anti-Aliasing Filter and Digital Pre-Filtering~~

[Comment to reviewers: It was suggested to remove this recommendation. While a physical anti-aliasing filter will smooth intensity gradients, a digital image pre-filter will remove high-frequency noise from the camera detector. Therefore, digital pre-filtering may still be beneficial even when a physical anti-aliasing filter is used.] ~~If a physical anti-aliasing filter was used during image acquisition, digital pre-filtering is not recommended.~~

5.2.3 Matching Criterion

The matching criterion is the heart of the DIC algorithm and—in conjunction with the subset shape function—mathematically describes optical flow or the conservation of intensity between the reference (undeformed) image and the series of deformed images. The basic matching criterion is the sum of square differences (SSD); more complex criteria, such as the normalized sum of square differences (NSSD) and zero-normalized sum of square differences (ZNSSD), are robust to changes in lighting that may occur during a test.

Tip 5.4 — SSD vs. ZNSSD

Correlation criteria that compensate for changes in lighting, such as the ZNSSD, are typically more robust in practical experimental situations than non-normalized criteria, such as the SSD. Moreover, the ZNSSD also performs equally well as the SSD in cases of steady and uniform light. One disadvantage of the ZNSSD, however, is that it is computationally more expensive, and thus may not be suitable for real-time applications.

5.2.4 Subset Shape Function

Some DIC software packages fix the subset shape function that is used, while others allow the user to choose this parameter. When selecting a shape function, there is a trade-off between noise filtering and accuracy. Lower order shape functions cancel more noise, but have less overall accuracy. Higher order shape functions (for example, quadratic and above) are more accurate, but the standard deviation of the solution will be higher. There are two outlooks on this trade-off: One view is to use large subsets with higher order shape functions. A second view is to use small, closely spaced subsets with low-order shape functions. An advanced user may explore the different options and combinations, and evaluate which is best for his or her application. See [1, 49, 50] for more information.

Local-Global Flag 5.1 — Element Shape Function

"Element shape function" in global DIC is analogous to "subset shape function" in local DIC. See Appendix C.4.1.

5.2.5 Interpolant

To obtain sub-pixel accuracy of DIC measurements, interpolation of image intensity between pixels is required. Therefore, the quality of interpolation has a significant influence on the precision and accuracy of DIC measurements. Most commercial DIC packages have optimized interpolants, and further refinement is an advanced topic. For more information, the reader is directed to [51] and [1, Sec. 5.6.1 (Interpolation Bias)].

5.2.6 Subset Size

Broadly speaking, a subset should be large enough to contain sufficient information such that one subset can be distinguished from all other subsets in the ROI. The rule of thumb is that the subset should contain a minimum of three DIC pattern features [1, Sec. 10.1.3.1], [31]. If the features are in the optimum 3–5 pixel size range and the feature density is approximately 50 %, then subsets of approximately 15×15 pixels[2] are required (i.e. a minimum of three transitions between dark and light pattern features in all directions is achievable). If the features are larger and/or the feature density is sparse, the subset size will need to be increased.

Recommendation 5.2 — Subset Size

A larger subset size of 21×21 pixels^2 is recommended as a more practical minimum size for typical DIC measurements [50]. This is true particularly if the DIC pattern size and density is variable and not constant over the entire ROI.

Tip 5.5 — Subset Size

Larger subsets typically result in lower displacement noise, but often at the cost of increased spatial smoothing. Higher-order subset shape functions can be used to compensate for subset smoothing [1, Sec. 5.3], [6, 52], but may lead to increased random errors [53].

Local-Global Flag 5.2 — Subset/Element Size

"Element size" in global DIC is analogous to "subset size" in local DIC. See Appendix C.4.2.

5.2.7 Step Size

The step size controls the density of points at which DIC data is computed and, to some extent, influences the spatial resolution of the measurements. Typically, a step size of one-third to one-half of the subset size is recommended, so that neighboring subsets partially overlap, though this value can vary widely depending on specific applications [24, 54]. As a general rule, if the overlap is larger than about one-third of the subset size, then neighboring data points are typically considered as no longer independent, and decreasing the step size further does not improve the spatial resolution of the measurements. However, a small step size (in conjunction with a small subset size) may allow data to be obtained close to the edge or other critical feature of the test piece, even if the overlap is large and neighboring subsets are not independent. Additionally, a small step size may be required to capture the peak *position* of a QOI (without interpolation) if it varies quickly across the ROI; see Example 5.1, specifically Fig. 5.4. (Note, however, that the peak *magnitude* of a spatially-varying QOI may still be damped or underestimated due to the low-pass-filter effect of DIC, if the spatial resolution is not sufficient to capture peaks in regions of high spatial gradients of the QOIs; again, see Example 5.1.) If the QOI varies slowly across the ROI, then a large step size can be used so as to reduce the number of data points, and thus reduce the computation time. (Even if the QOI varies slowly across the ROI, a maximum step size equal to the subset size is suggested, to generate quasi-continuous field data without interpolation.) Additionally, the step size also influences the Virtual Strain Gauge size (Sec. 5.3.3.1 and Sec. 5.4.5).

Local-Global Flag 5.3 — Step Size

While in local DIC, subsets can overlap, for global DIC, elements are continuous with no overlap. Therefore, only the element size is needed to characterize the finite-element mesh, and there is no equivalent term for step size in global DIC.

5.2.8 Thresholds

DIC software typically allows the user to select different thresholds that are used to determine the quality and confidence of the displacement results for each subset. The thresholds available are software-dependent, but two main thresholds include the value of the matching criterion and the epipolar error. The value of the matching criterion is a measure of how well each subset was matched between the reference image and a deformed image (or between the left and right cameras for stereo-DIC). The epipolar error, which applies only to stereo-DIC, is a measure of how well the correlation results agree with the stereo calibration. Any displacement results that are above the threshold values are removed from the reported results. Increasing the threshold values allows more displacement results to be retained, but at the cost of more uncertainty in the results.

Local-Global Flag 5.4 — Thresholds

Depending on the software implementation, individual elements may or may not be discarded based on thresholds such as for the matching criterion and epipolar error. In the case they are not discarded, one can still evaluate the magnitude of the gray level residual or matching criterion as a metric for the quality and confidence of the displacement results. See Appendix C.5.1.

5.2.9 Initial Guess

In many cases, the DIC software can correlate images based solely on the image intensity gradients resulting from the DIC pattern and, for stereo-DIC, the calibration. However, in some circumstances, an initial guess needs to be supplied in order to initialize the correlation process. An initial guess may be required if, for instance, the displacement between consecutive images is large, as mentioned in Tip 2.6.

The details of how an initial guess is generated are software-specific. Some methods of providing an initial guess include:

- The user manually identifies the approximate location of a material point in each of the images.
- The image size is reduced by binning or resampling; these reduced images are correlated to provide initial guesses for the main correlation of the full-size images.
- The matching criterion is computed as the subset is translated in integer pixel displacements in the deformed image; the location of the best matching criterion value is taken as the initial guess.
- Other, more sophisticated methods of estimating initial guesses also exist [55, 56].

5.3 User-Defined Post-Processing Parameters

5.3.1 Coordinate System

The default coordinate system of the DIC data depends on the software. For 2D-DIC, the X and Y axes are typically aligned with the horizontal and vertical directions of the image, respectively. For stereo-DIC, common options include basing the coordinate system off of the left camera position/orientation, or centering the coordinate system between the two cameras. For flat test pieces, a "best-plane fit" is often used, where the Z axis is set to be perpendicular to a plane that is fit to the 3D point cloud describing the undeformed test piece surface; then, the X axis is aligned with the horizontal direction of the image and the Y axis is perpendicular to the Z and X axes. After performing the image correlation, the user may define a DIC coordinate transformation in order to align the coordinate system to physically meaningful axes.

Recommendation 5.3 — Coordinate System

The default coordinate system may or may not correspond to a physically meaningful coordinate system. Additionally, if there are multiple ROIs of a test piece with a complicated geometry, different coordinate systems may be needed for different ROIs. Therefore, it is generally recommended to define an appropriate, physically meaningful coordinate system for every DIC analysis. As described in Recommendation 3.3, placing fiducials on the test piece assists in defining a coordinate system.

5.3.2 Data Filtering

After the initial correlation process, the DIC data may be filtered to reduce noise. There are innumerable methods for filtering the data, including methods in the temporal domain, spatial domain, and/or frequency domain. If any type of filtering is performed, this information should be reported, as specified by the reporting requirements in Sec. 6.2.

Caution 5.3 — Data Filtering

While filtering may reduce noise or variance errors, it could also introduce bias errors. See Sec. 5.4.4 for more information on evaluating the trade-off between noise and bias errors.

5.3.3 Strain Calculations

There are many different approaches to calculating strain from displacements, depending on the specific DIC software that is used. For a list of DIC software packages, see the iDICs website at `https://idics.org/resources/`. In each approach, there are different user-defined parameters that can be selected in the software. Refer to the user manual for explicit details about how strains are computed in the DIC software of choice. In this section, the virtual strain gauge is defined, and several representative examples of strain calculation methods are briefly described.

5.3.3.1 Virtual Strain Gauge (VSG)

One common and key element of all the approaches to strain computation is the virtual strain gauge (VSG). The VSG, broadly speaking, is the local region of the image that is used for strain calculation at a specific location. It is analogous to — though not directly equal to — the physical area that a foil strain gauge covers. The strain computed in DIC software is the average or weighted average of the strain within the VSG.

The exact size of the VSG depends on the method of strain computation used in the specific software. Even for a given method of strain computation, the exact size of the VSG is not well defined. However, there are several key variables that affect the VSG size, including step size, subset size, subset shape function, element size, element shape function type, strain window, strain shape function, pre-filtering of the displacements, post-filtering of the strains, and filter window. Because many of these user-defined parameters are specified in terms of pixels, the VSG size can vary across the test-piece ROI, if the image scale varies (e.g. due to the stereo-angle). Spatial resolution of strain measurements is closely related to the VSG size, in addition to other DIC processing parameters. Sec. 5.4.5 provides more information about the effect of the VSG size on the noise and bias of strain measurements.

5.3.3.2 Descriptions of Select Strain Calculation Methods

Here, four general approaches for strain computation — representative of different approaches implemented in different DIC software packages — are briefly described. The effects of different user-defined parameters on the VSG size are highlighted.

5.3.3.2.1 Subset Shape Function

One approach is to compute the strain directly from the subset shape function and the deformed subset shape. In this method, the VSG size is approximately equal to the subset size, giving rise to one of the smallest VSG sizes of all the strain computation methods. Additionally, no pre-filtering is applied to the displacements. The small VSG size and the lack of pre-filtering of displacements leads to high spatial resolution of the strain measurements, but noisy strain results.

After strains are calculated, they may be post-filtered to reduce the noise. A common type of post-filter is the mean of a local set of data points, often with a Gaussian weighting function. The region of the data points that is included in this filter is called the filter window. The VSG size can then be approximated by Eqn. 7.2 (Sec. 7.2).

5.3.3.2.2 Finite-Element Shape Functions

A second approach closely follows the strain calculations used in finite-element analysis. A triangular mesh is defined on the ROI of the reference image, using the displacement data points (provided at the center of the subsets) as the nodes of the mesh. Using finite-element shape functions defined over each triangular element, the strain is computed from the deformed shape of each element. If a global DIC approach has been used, the computation can be done directly on the pre-existing finite elements (see Appendix C.5.4). At this point, the VSG size is small, approximately equal to the size of the triangular elements (which is governed by the step size) plus the size of the subset. If no pre-filtering of the displacements was performed, the strain results from this method are usually noisy. Therefore, the strains are often post-filtered to reduce the noise. A common type of post-filter is the mean of a local set of data points, often with a Gaussian weighting function. The region of the data points that is included in this filter is called the filter window. The VSG size can then be approximated by Eqn. 7.2 (Sec. 7.2).

As a slight variation to the above approach, instead of computing the strain on each triangular element individually using only the three nodes of the element, the strain can be computed in a least-squares sense over a larger (i.e. hexagonal) region covering several triangular elements. This larger region is called the strain window, and the VSG size be approximated by Eqn. 7.2 (Sec. 7.2). In the least-squares regression, a weighting function may be applied to the displacement data points contained within the strain window, for instance with a Gaussian distribution centered at the center of the strain window and decaying towards the edges of the strain window. By computing the strain over a larger strain window using more data points, the strain results are less noisy, and post-filtering of the computed strains may not be necessary.

5.3.3.2.3 Strain Shape Function

A third approach is to fit a strain shape function to the displacements, which provides an analytical description of the displacement field [57]. The strains are then computed from the spatial derivatives of this analytical equation. Fitting the displacements to the strain shape function also serves to filter the displacements; thus, this fitting process can be considered as pre-filtering or smoothing the displacements before calculating the strains. The strain shape function is typically a polynomial or spline fit, and the order of the strain shape function effects the spatial resolution of the strain measurements.

The local region of the data points that is included in the fit is called the strain window. Typically, strains are computed at the center of the strain window. A weighting function may be applied to the displacement data points contained within the strain window, for instance with a Gaussian distribution centered at the center of the strain window and decaying towards the edges of the strain window. The VSG size is approximated by Eqn. 7.2 (Sec. 7.2).

5.3.3.2.4 Spline Fit

A fourth approach to strain calculations is to fit a spline to the entire displacement field, over the entire ROI. This approach is similar to the use of strain shape functions, except that here, the fit is global rather than local. This spline fit provides an analytical description of the strains over the entire ROI, which can be evaluated at any point in the ROI. Thus, strain measurements are not limited to the original DIC data point locations at the center of the subsets. The VSG size is less clearly defined, since there is no filter window or strain window, but it is related to the step size, subset size, element size, element shape function type and order of the spline.

5.3.3.2.5 Local Hermite Method

A fifth approach is to calculate the strain based on regularization by finding a best fitting surface to approximate the true displacement field concerning both the fitness and smoothness of resultant displacement/strain field. After using the fitting function, such as the Hermite shape function or polynomial, the regularization (for example the Tikhonov regularization) is utilized to tackle the ill-posed inverse problem in traditional least-squares regression, which comprises an additional regularization matrix and a regularization parameter. The regularization matrix is defined by summation of squared partial differential of fitting function, and the regularization parameter is normally determined by the generalized cross-validation (GCV) function. Thus, the strain is obtained by differentiation of the fitted surface.

This approach includes both global and local versions. The global method [58, 59] defines the fitting function typically with Hermite finite elements on the whole ROI. It involves meshing and global regularization matrix assembly processes, and the strains are computed in on the entire ROI at once. For local methods [60, 61], as the special cases of global methods with only one element (also called the strain window), the generation of the regularization matrix is simple, and the strain is computed at the central point in the strain window, with strain computed at each data point in the ROI individually. In local methods, the parameters that effects the strain results include the order of the fitting function and window size.

5.4 Measurement Uncertainty

[Comment to reviewers: The Measurement Uncertainty working group, chaired by Thorsten Siebert, is currently developing a complimentary guide on specifically on Measurement Uncertainty (MU) for DIC measurements. Once the MU guide is complete and published, we will update this section accordingly.]

5.4.1 Overview

There are two types of errors of DIC measurements, i.e. variance errors and bias errors. Variance errors (also called noise) refer to random errors centered with a mean about the true value of a QOI. Bias refers to an offset of the mean from the the true value. The main sources of noise in DIC measurements are camera noise, and matching errors during the correlation process. Bias can be introduced by smoothing over peaks in the QOI in regions of high spatial gradients, uncorrected lens distortions, improper camera calibration (e.g. if there was relative motion between cameras in a stereo system after calibration but before the mechanical test), and out-of-plane motion in 2D-DIC measurements, to name a few sources. Establishing the uncertainty of QOIs — considering both bias and noise errors — is critical for intelligent assessment and use of DIC results. Without uncertainty quantification, it is impossible to know if a reported QOI value is significant and relevant, or if it is the result of random noise and/or bias, and thus meaningless.

Sec. 5.4.2 and Sec.5.4.3 describe some methods of quantifying noise and bias errors of DIC measurements. However, bias is often not known, and variance errors computed from static images acquired *prior* to the test may not fully represent the variance errors present *during* the test. Therefore, the metrics available to a DIC practitioner for quantifying uncertainty often produce a *minimum* uncertainty of a QOI, rather than the true uncertainty. Several options for metrics defining the uncertainty are suggested here, but other definitions exist for specific applications and for different QOIs. The key component, though, is to justify and document (see Sec. 6) some metric and value for the uncertainty of the QOIs.

5.4.2 Variance Errors

The term "variance error" is used interchangeably with "noise", and the process of quantifying the variance errors is often called a noise-floor analysis. The basic idea of a noise-floor analysis is to correlate undeformed (i.e. static and rigid-body-motion) images of a DIC pattern that were acquired under the same conditions as the test images. With no applied force or deformation on the test piece, all measured QOIs requiring deformation (e.g. strains) are errors. Any of those QOIs measured in the actual mechanical test that are smaller than the QOIs measured from the static images are indistinguishable from the noise.

Recommendation 5.4 — Variance Errors and Camera Noise

A significant source of variance errors in DIC measurements is driven by camera noise. Noise of the camera detector, i.e. fluctuations over time in the gray level intensity of a pixel observing a fixed object, directly contributes to noise in DIC results. Therefore, it can be useful to quantify the camera noise independent of quantifying the noise of the DIC results. This is typically only necessary when evaluating new hardware for its suitability for DIC (see Sec. 2.2.1). In the end, the noise-floor of the QOI is the critical metric, so one may choose to omit characterizing the noise of the camera itself.

5.4.2.1 Iterations of the Noise-Floor Evaluation

Evaluating the noise-floor is an iterative process that is typically performed several times, using sequentially more robust analysis procedures and metrics, during the design and execution of the DIC measurements. A rudimentary evaluation can be completed during the preliminary design of the measurements, to aid in the selection of the camera and lens, choice in patterning technique, etc. (Chapter 2). A second quick evaluation can be done during the pre-calibration review of the DIC system (Sec. 3.1.6.4), or the final review of the system (Sec. 3.3.3.1), before the mechanical test is performed. A third evaluation of the noise-floor is performed iteratively during the processing of DIC images after the mechanical test is performed, in order to evaluate the effect of user-defined parameters, and the trade-off between noise and bias (see Sec. 5.4.4).

For reporting purposes, the final, most thorough evaluation of the noise-floor must be done using the same conditions as the mechanical test, both in terms of physical conditions (e.g. camera and lens selection, lighting, camera temperature, cooling or mixing fans, test machine powered on) as well as data processing procedures (i.e. prefiltering of images, subset size, step size, element size, element shape function, VSG size, temporal or spatial filtering of data, etc.). This means that the same user-selected DIC settings that are used for the analysis of the test piece images during motion/deformation must also be used for the analysis of the noise-floor images. Therefore, the final noise-floor analysis is typically completed *after* the mechanical test images are analyzed, but using images that were acquired immediately *before* the mechanical test.

5.4.2.2 Temporal vs. Spatial Variance Errors

Two different metrics can be used to quantify the variance error of QOIs: a spatial standard deviation and a temporal standard deviation. To quantify the spatial variation of the QOI, compute the standard deviation of the QOI for each image. Then average this spatial standard deviation over time for all the undeformed images. To quantify the temporal variation, compute the standard deviation of the QOI for each data point over time. Then average this temporal standard deviation for each data point over all the data points in the ROI of the image. Note that for an accurate evaluation of the temporal noise, the static images must have been acquired at the same frame rate as the test images, as described in Recommendation 3.13.

While seemingly similar at first glance, these two different metrics of error provide different views of the noise-floor, emphasizing either spatially-varying or temporally-varying noise. It is recommended to compute both the spatial and the temporal standard deviation and evaluate if one is significantly larger than the other. However, the spatial and temporal standard deviations are typically similar, and either a single metric or the average of the two metrics can be selected to quantify the noise-floor.

5.4.2.3 Directional Components of the Noise-Floor

Typically, the standard deviation is similar between all directional components of a QOI (e.g. U and V as the two in-plane displacement components, or ϵ_{xx} and ϵ_{yy} as the two normal strains). It is recommended to compute the standard deviation for the QOI in each direction, though, and select either the maximum or the average between the directions.

Tip 5.6 — Typical Displacement Noise-Floor

As a general rule-of-thumb, for a well-controlled environment and an appropriate pattern (as described in Sec. 2.3), the noise-floor for in-plane components of DIC displacements, U and V, should be ca. 0.01 px. For stereo-DIC, the noise-floor for the out-of-plane displacement component, W, is normally approximately three times higher, or ca. 0.03 px. The noise-floor in engineering units can be computed by scaling these values by the image scale of the system.

5.4.2.4 Quantifying Acceptable Noise-Floor for the Application

Given the standard deviation of the QOI, determine the noise-floor as a function of the standard deviation, using the experience of a subject matter expert. For example, some applications may require that all measurements with magnitudes of variation below three times the standard deviation be considered noise; other applications may loosen the requirement, so that only measurements with magnitudes of variation below one standard deviation be considered noise.

Depending on the application, different amounts of rigor may be employed when quantifying the noise-floor. Some examples include:

- **Abbreviatednoise-floor:** This option is performed with static images, typically acquired immediately prior to performing the mechanical test, and it captures primarily the effect of camera detector noise. It is the quickest evaluation of the noise, but also the least conservative. Typically, true noise levels of QOIs extracted from the DIC measurements during the mechanical test are larger than the noise-floor computed from only static images. That is, an abbreviated noise-floor evaluation provides a lower bound on the true QOI noise or variance errors.

- **Extendednoise-floor:** This option is performed with rigid-body motion images. In addition to capturing effects of camera detector noise, it also exercises the lens distortion model, as described in Sec. 3.3.2.1. An extended noise =-floor is more time-consuming to perform compared to an abbreviated noise-floor, but it also provides a more accurate estimation of the noise-floor. One drawback, however, is that it does not account for pattern evolution (and possible degradation) that occurs during the mechanical test.

- **Deformedpatternnoise-floor:** This option strives to account for the effect of DIC pattern evolution (and possible degradation) that occurs during the mechanical test. Depending on the specific details of the application, there are different ways to evaluate the noise-floor using the deformed DIC pattern. One option is to acquire a series of rigid-body motion images using the deformed test piece after the mechanical test is finished. Another option is to quantify the variation in the strain field when the strain is homogenous and uniform, e.g. for a tensile dog bone with a constant gauge section before any localization occurs. The deformed pattern noise-floor is the most representative value of the variance errors for the QOIs extracted from the mechanical test. For strains, experience has shown that it can be orders of magnitude higher than the abbreviated noise-floor or extended noise-floor, for some applications.

In summary, there are many different options a DIC practitioner has when quantifying the noise-floor of the QOIs. There is no single correct procedure, as many choices are application dependent. This section provides many factors one should consider when computing the noise-floor. In the end, though, the critical factor is that a noise-floor should be computed and reported with the DIC measurements, and the process used to compute the noise-floor should also be reported.

5.4.3 Bias Errors

Bias errors are often difficult to quantify, because the true value of a QOI is typically not known. However, some sources of bias can be evaluated as described below. It is important to note, however, that these evaluations are necessary but not sufficient to elucidate bias errors. Said another way, some bias errors may be detected through these evaluations, and if bias errors are detected, they should be reported; however, even if no bias errors are detected, unknown bias errors may still exist!

One metric of bias error of the QOI is the mean of the QOI from static images. A mean that changes over time could indicate a bias due to camera drift, heating of the camera (i.e. the cameras had not yet reached steady state during the camera warm-up), heat waves, vibrations, etc.

Bias errors due to uncorrected lens distortions can be evaluated from rigid-translation images, if the rigid-body motion is approximately the same magnitude as the test piece motion and/or deformation during the actual test. Bias due to uncorrected lens distortions will manifest as an elliptical shape in the contour plots of strains (and of the displacements if the mean displacement or known applied displacement is subtracted from the field), as shown in Fig. 3.6. This type of bias is typically lower in the center of the FOV and higher near the edges, due to the mostly radial form of lens distortions.

For 2D-DIC, the bias error due to out-of-plane motion should be evaluated (see Example 2.1). Using rigid-body, out-of-plane translation and rotation images, compute the QOI (here, it is assumed that the QOI is in-plane strain) as a function of applied translation/rotation. The strain should be zero for rigid-body motion, so any strain measured is a combination of bias and noise. Estimate the amount of out-of-plane translation/rotation that may have occurred or did occur during the test and report this. Compare the estimated bias error due to out-of-plane motion to the baseline noise-floor computed from static images (Sec. 5.4.2). If the bias error is larger than the variance errors, consider revising the mechanical test setup to reduce out-of-plane motion.

Bias can also be introduced into the QOI as a result of low-pass filtering, in the spatial domain, caused by the choices of user-defined parameters. This type of bias is described in more detail in Sec. 5.4.4. Finally, other factors, such as interpolant, aliasing, and noise, may cause spatially periodic bias errors that may not be visible in static images of an unloaded and stationary test piece [6, 47].[24]

5.4.4 Trade-Off Between Noise and Bias

When selecting user-defined parameters (Sec. 5.2 and Sec. 5.3), there is often a trade-off between noise in the measurements and bias due to over-smoothing of the data. Large subset/element sizes, low-order subset/element shape functions, large VSG sizes, pre- or post-filtering of the data, etc. all reduce noise in the measurements, but at the expense of acting as low-pass spatial filters that potentially introduce bias to the measurements. Therefore, when selecting user-defined parameters, it is important to evaluate their effects on both noise and bias errors. Often, the final selection of parameter values is a compromise between noise and bias errors [62, 63]. The choice between noisier but unbiased measurements versus smoother but underestimated measurements is application dependent; expert judgment is often required to determine which set of parameters produces appropriate results for a given test. In Sec. 5.4.5, a methodology and example are presented for evaluating the trade-off between noise and bias of strain, since strain is one of the most common QOIs of DIC measurements. Similar methods, though, can be applied to other QOIs.

The discussion of noise versus bias is also closely tied to the discussion of the spatial resolution of DIC measurements. Defining the spatial resolution of DIC measurements is a current topic of interest for iDICs, and iDICs is actively exploring this concept. For more information on the trade-off between noise and bias, as well as current efforts on defining spatial resolution, see [44].

[24] For 2D-DIC, bias errors due to poor interpolants or aliasing may be evaluated by translating a flat test piece out-of-plane towards/away from the camera. This is an advanced topic and is not covered in this edition of the guide. For stereo-DIC, there are currently no standard procedures for detecting or evaluating these types of bias errors.

5.4.5 Virtual Strain Gauge Study

Strain is a derived quantity, related to the spatial variation of the displacements. There are many different approaches to calculating strain from displacements, depending on the specific DIC software that is used, as described briefly in Sec. 5.3.3. One common feature is the requirement that the user select, either directly or indirectly, the size of the VSG. A virtual strain gauge study is the process used to determine an appropriate and acceptable VSG size. It also elucidates if the peak strain magnitude is captured in regions of high spatial strain gradients, and aids in the determination of what the optimum balance is between capturing the peak strain magnitude (i.e. minimizing bias due to over-smoothing) and improving the strain resolution (i.e. minimizing the variance errors). Some DIC packages automate this process, while with others, the user must perform it manually.

Example 5.1 — Virtual Strain Gauge Study

[Comment to Reviewers: This VSG study example has been significantly reworked from the VSG study present in Edition 1 of the Good Practices Guide. For editorial simplicity, I did not highlight everything, but this example should be reviewed as part of Edition 2 revisions/additions.]

In this example, a VSG study is performed using the Stereo-DIC Challenge images from Sample 5: Tensile-Experimental, which can be downloaded freely at `https://idics.org/challenge/`. An overview of the experimental setup is reported in Table ?? following the reporting guidelines in Sec. 6.1; more details are found in the overview documents that accompany the images.

Table 5.1: DIC hardware parameters for the VSG study

Camera	FLIR (formerly PointGey) Grasshopper 2 (Gras-50S5M)
Image Size	5 MP, 2448×2048 px^2
Lens	Edmund Optics, DG Series
Focal Length	35 mm
Aperture	f/8 (approximate)
Field-of-View	36.8×30.8 mm^2 (approximate)
Image Scale	66.5 px/mm (approximate)
Stereo-Angle	28^o (approximate)
Stand-Off Distance	190 mm (approximate)
Image Acquisition Rate	1 Hz
Exposure Time	10 ms (approximate)
Patterning Technique	Base coat of white paint (SEM primer) with black features on top
Pattern Feature Size	7 px (approximate)

The basic steps for a VSG study are as follows:

1. Perform an initial DIC analysis on all images of the mechanical test using predetermined DIC user-defined parameters, based on vendor defaults or past experience and expert judgment.

2. Select the reference image and the image of highest strain gradients determined in the pre-

vious step. See Fig. 5.2. Analyze these images with different DIC settings, varying the VSG size.

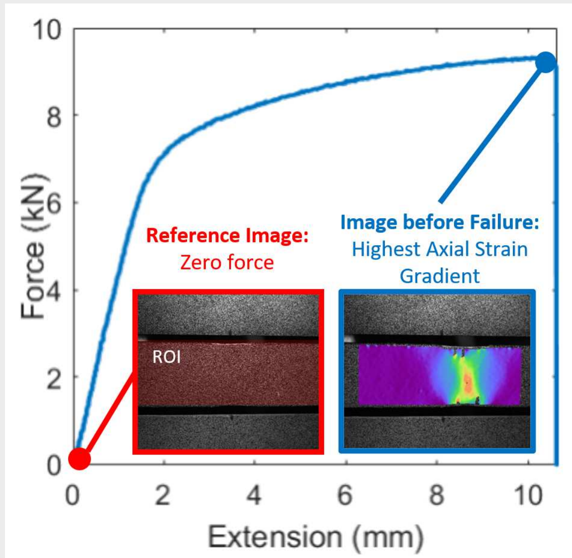


Figure 5.2: Example force-extension curve, where the reference image is selected at the beginning (zero force) and the image before failure is selected as the image with the highest axial strain gradient.

Tip 5.7 — Parameters Affecting VSG Size

There are many parameters that affect the VSG size, as described in Sec. 5.3.3.1. In this example, a simplified approach is used, where the subset size and step size were selected based on the recommendations in Sec. 5.2.6 and 5.2.7, respectively, and only the strain or filter window was adjusted. However, some applications may require a more complete investigation of more or all of the user-defined parameters that affect the VSG size, often informed by the QOI of interest.

Local-Global Flag 5.5 — VSG Size

For details on the VSG size for global DIC, see Appendix C.5.4.

Recommendation 5.5 — QOI for VSG Study

It is recommended to investigate all three strain components (i.e. the two normal strains ε_{xx} and ε_{yy}, and the shear strain ε_{xy}). However, if only one strain component is the main QOI, an abbreviated VSG study can be done. In this example, only the axial normal strain, ε_{xx}, is investigated.

3. Extract a line cut through the region of highest strain gradient. Plot the strain along the line for each of the analyses performed in the previous step. See Fig. 5.3.

   As the VSG size decreases, the maximum strain magnitude along the line cut will typically increase. When the strain magnitude no longer increases as the VSG size decreases, the strain magnitude is said to be converged. Convergence is discussed more in Step 5.

Caution 5.4 — VSG Study Line Cut

Ensure that the line cut does not bridge a crack in the test piece. Computing strain across a crack is not physically meaningful.

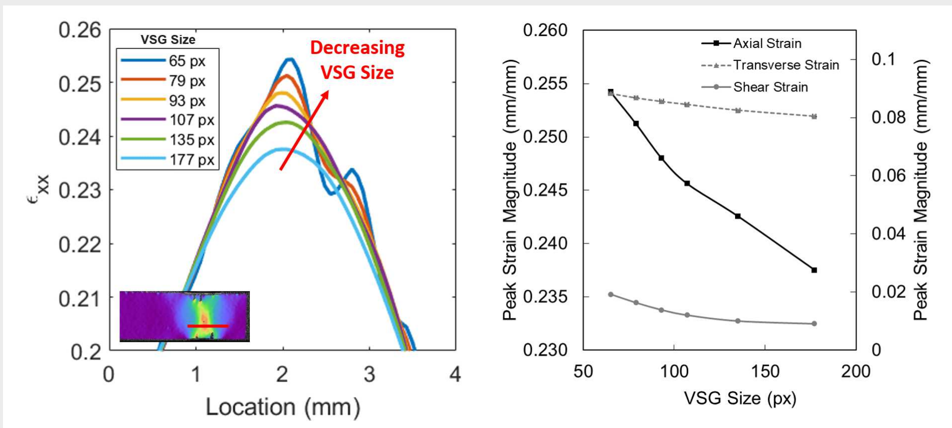


Figure 5.3: Left: Axial strain as a function of location along a line cut (inset) for the image with the highest strain gradient. Right: Peak strain magnitude as a function of VSG size. As the VSG size decreases, the peak magnitude increases.

Caution 5.5 — Noise on Peak Strain Magnitude

The measured peak magnitude is a combination of the true peak magnitude of the underlying strain field and the measurement noise. Therefore, the measured peak magnitude for small VSG sizes may be artificially inflated due to a higher noise-floor. See Step 4 for more information on the noise-floor.

Additionally, the measured location of the peak may be incorrectly displaced from the true location of the peak, if the noise causes spurious peak values.

Caution 5.6 — Peak Strain Magnitude Dependence on Step Size

There is one aspect of the choice of step size and strain calculation method that is often not considered. Typically the strain values are only calculated at the center of each subset, which are spaced at the step size. Unfortunately, this can result in failing to sample the maximum strain magnitude location, if the step locations straddle the actual peak.

To illustrate this concept, Fig. 5.4 shows a hypothetical true strain profile in black. When a large step size is used (11 px in this example), the strain signal is undersampled. Depending on the starting location of the first data point (i.e. the "offset"), the true peak value (in black) could either be captured (red curve) or missed (yellow curve). Capturing the peak in this undersampled situation cannot be guaranteed *a priori* and is a matter of chance or luck. When a small step size is used (3 px in this example), the sampling is sufficient, and the peak is captured well (green curve).

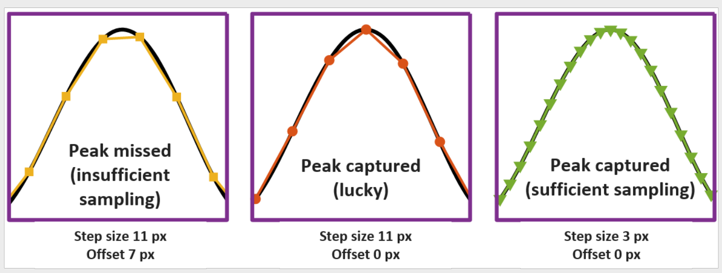


Figure 5.4: Schematic showing the effect of step size on the strain peak magnitude.

Although different selections of subset size, step size, and strain or filter window would change the value of this potential bias in the result, all systems that measure and report strains only at the step size interval risk under-reporting the magnitude of the largest strain in the underlying images, due to under-sampling. This uncertainty scales with the magnitude of the strain peak and the step size.

4. Compute the noise floor for each of the analyses with different VSG sizes, using the same parameters used in Step 3.

   Capturing images for the noise floor is described in Sec. 3.3.1. The images could be static images or rigid-body-motion images of the test piece itself or a coupon with the same patterning method. These images are typically captured either immediate before or immediately after the mechanical test, with the same (or as similar as possible) environmental conditions as the mechanical test.

   There are many factors to consider when quantifying the noise; see Sec. 5.4.2 for more details. In this example, an abbreviated noise-floor evaluation was performed for demonstration purposes. Ten static images, captured at the beginning of the mechanical test before force was applied, were analyzed with the different VSG sizes. Then, one standard deviation of all points in the ROI for all 10 static images was computed and taken as the noise-floor. The noise-floor is shown in Fig. 5.5 as a function of the VSG size. As the VSG size decreases, the noise-floor will typically increase.

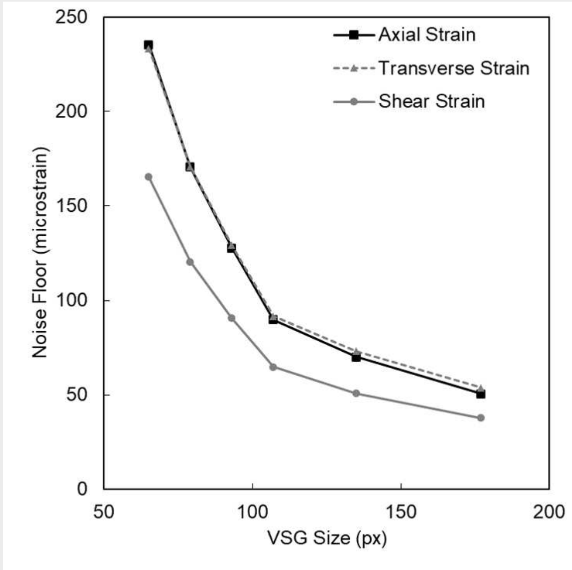


Figure 5.5: The noise-floor computed from 10 static images as a function of VSG size. As the VSG size increases, the noise-floor decreases.

5. Plot the peak strain magnitude from Step 3 versus the noise-floor from Step 4, as shown in Fig. 5.6, to visualize the trade off between noise and bias errors.

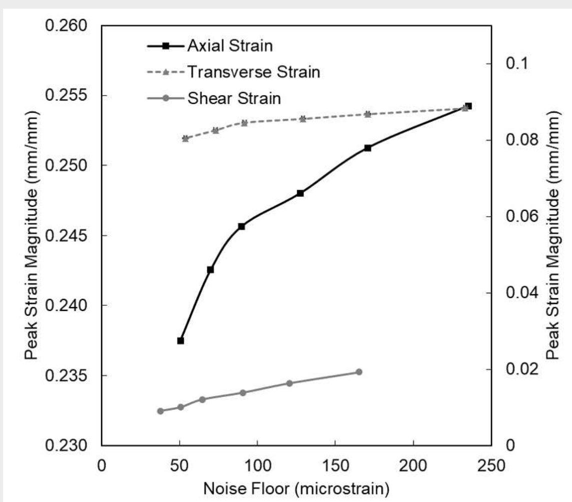


Figure 5.6: The peak strain magnitude, for all three in-plane strains, as a function of noise-floor magnitude.

In this example, the axial strain continues to increase as the noise increases (VSG size decreases), which is an example of the strain field not converging. If the maximum strain magnitude never converges, even with the smallest VSG allowed by the software, then the actual maximum strain magnitude is unknown. At best, one can report that the actual strain magnitude is greater than or equal to the maximum measured strain magnitude. That is, the reported strain is a lower bound on the actual strain magnitude.

Tip 5.8 — VSG Size Convergence

If the smallest VSG allowed by the software is not sufficient, the test could be repeated with a smaller FOV (i.e. higher magnification resulting in larger image scale). For a given set of user-defined parameters such as subset size, step size, strain or filter window size, etc. — all defined in terms of pixels in the DIC software — larger image scale (i.e. higher magnification) would produce a smaller physical VSG size. See Sec. 2.1.8 for more information.

If the maximum strain magnitude converges with further decreases of the VSG size, then the actual maximum strain magnitude has been captured within the ultimate spatial resolution of the DIC system.[a] In this example, the transverse strain magnitude does plateau with increasing noise (decreasing VSG size); if the transverse strain was the most important QOI, the user-defined parameters may be deemed sufficient.

The final decision on which user-defined parameters and VSG size to use is application-dependent and often a matter of expert judgment. If capturing the highest strain peak magnitudes in regions of high strain gradients is critical for the DIC analysis, then a small VSG may be the best choice, even if the noise is large. On the other hand, if there are no high strain gradients, and/or a smoother strain field and/or reduced noise are more important than knowing the maximum strain at locations of high strain gradient, then a larger VSG may be the best choice. Alternatively, a combination of different VSG sizes for different portions of the test could be appropriate (e.g. a large VSG size early in the test when the signal-to-noise ratio for strains is low and strain gradients are small, and a small VSG size later in the test, when the strain signal-to-noise ratio is higher, and significant strain gradients have developed).

Table 5.2: DIC analysis parameters for the VSG study

DIC Software†	[Manufacturer and Version number]
Image Filtering†	[Not reported here]
Reference Image	Single reference image (standard correlation)
Interpolant†	[Not reported here]
Matching Criterion	Zero-normalized sum-of-square differences (ZNSSD)
Subset/Element Size	37 px (0.56 mm)
Step Size	7 px (0.11 mm)
Subset Shape Function	Affine
Strain Window	11 data points
Virtual Strain Gauge Size††	107 px (1.61 mm)
Strain Formulation	Hencky
Strain Noise-Floor	90 µm/m for ε_{xx} 92 µm/m for ε_{yy} 65 µm/m for ε_{xy}

†These parameters are vendor-specific and thus not included in this example.

††The VSG size was estimated using Eqn. 7.2 (Sec. 7.2).

In this example, the final analysis parameters are reported in Table 5.2 following the reporting guidelines described in Sec. 6.2. These parameters were selected for illustrative purposes, to balance bias and noise errors: with a VSG size of 107 px (1.61 mm), the shear strain is nearly converged at a peak magnitude of 0.012 ± 65 mm/mm, and the reduction in noise for larger VSG sizes has diminishing returns. Note, however, that the axial and transverse strains are not converged, and thus the peak magnitudes of 0.25 ± 90 mm/mm and 0.08 ± 92 mm/mm, respectively, are lower bounds on the true peak magnitudes.

[a]For example, the macroscopic strain of a metal test piece may converge at the continuum level, yet highly-localized, microscopic strains of higher magnitude may exist at grain boundaries. This consideration is outside the scope of this edition of the guide.

6 — Reporting Requirements

With all the variables that must be selected in a mechanical test with DIC measurements, such as parameters of the physical system (i.e. camera, lens, patterning method, etc.) and parameters of the data analysis process (i.e. subset/element size, virtual strain gauge size, etc.), justification and documentation of the choices made is critical. The lists below present the minimum reporting requirements, as well as suggested and more detailed reporting recommendations. All documentation of DIC data — both internal reports and published journal articles — should contain this information. While the information may be documented in any format, one option is shown in Table 6.1 and Table 6.2. Note that more information may be necessary depending on the specific application.

Tip 6.1 — Application-Dependent Reporting Requirements

Depending on the application of the DIC data, some of the reporting recommendations may not be necessary, while others not listed here may be important. The key, though, is to document all relevant information!

Table 6.1: Example table that satisfies the basic reporting requirements for the DIC hardware parameters. Note that more information may be necessary depending on the specific application.

Camera	[Manufacturer and Model]
Image Size	2448×2048 px^2
Lens	[Manufacturer and Model]
Focal Length	35 mm
Aperture	f/8
Field-of-View	36.8×30.8 mm^2
Image Scale	66.5 px/mm
Stereo-Angle	25°
Stand-Off Distance	190 mm
Image Acquisition Rate	15 Hz
Exposure Time	50 ms
Patterning Technique†	Base coat of white spray paint with blank ink stamped speckles
Pattern Feature Size	5 px (0.2 mm)

†A more complete description of the patterning technique may be appropriate in the main text.

Table 6.2: Example table that satisfies the basic reporting requirements for the DIC analysis parameters. Note that more information may be necessary depending on the specific application.

DIC Software	[Manufacturer and Version number]
Image Filtering	Gaussian filter with a 3×3 px^2 kernel
Reference Image	Single reference image (standard correlation)
Interpolant	Bi-cubic spline
Matching Criterion	Zero-normalized sum-of-square differences (ZNSSD)
Subset/Element Size	21 px (0.84 mm)
Step Size	7 px (0.28 mm)
Subset Shape Function	Affine
Strain Window	15 data points
Virtual Strain Gauge Size	119 px (4.76 mm)
Strain Formulation	Green-Lagrange
Strain Noise-Floor	250 µm/m

6.1 DIC Hardware Parameters

6.1.1 Required

- Camera Manufacturer and Model, and Image Size
- Lens Manufacturer and Model, and Focal Length

  Note 1: If lens has a variable focal length, report both range and focal length used.

- FOV
- Image Scale

  Note 1: In stereo-DIC, where the cameras are at an angle to the test piece, the image scale is not constant across the FOV, and can be different in the two cameras. Therefore, the image scale of the ROI of the image should be reported, either as the average for the two cameras, if the scale is nearly the same, or for each camera individually, if the scale is significantly different in the two cameras.

- Stereo-Angle

  Note 1: Applicable for stereo-DIC; not applicable for 2D-DIC.

- SOD
- Image Acquisition Rate
- Exposure Time
- Patterning Technique
- Approximate Pattern Feature Size

  Note 1: Specify method used to determine feature size. Note that both light (white) and dark (black) regions are considered features.

6.1.2 Recommended

- Aperture
- Image Noise

6.2 DIC Analysis Parameters

6.2.1 Required

- DIC Software Package Name and Manufacturer

  Note 1: If an independently developed (non-commercial) DIC code is used, it is strongly recommended to verify the code using images from the DIC Challenge [44] (https://sem.org/dic-challenge/). Any subsequent documentation of DIC measurements that use the code should refer to this verification.

- Image Filtering, if applied
- Reference Image
- Interpolant
- Matching Criterion
- Subset Size

  Note 1: Preferably, report both in terms of pixels and in terms of physical units (e.g. millimeter) by scaling based on the image scale.

- Step Size

  Note 1: Preferably, report both in terms of pixels and in terms of physical units (e.g. millimeter) by scaling based on the image scale.

- Subset Shape Function (e.g. affine, quadratic)

Local-Global Flag 6.1 — Reporting Requirements

Subset size, step size, and subset shape function are all specific to local DIC. If a global formulation is used, report the analogous parameters of element size and element shape function. Since element size may vary across the ROI, report the average and standard deviation, or the average and minimum/maximum, and/or provide an image showing the finite-element mesh. See Appendix C.4 for more information.

- Data Processing and Filtering for QOIs

Recommendation 6.1 — Reporting Requirements for Strain

Strain is one of the most common QOIs. Typical parameters to report include:

- Pre-filtering of displacements (spatial and/or temporal), if applied
- Strain formulation (i.e. Lagrange, engineering, logarithmic etc.)

  - Strain window
  - Virtual strain gauge size

    Note 1: Preferably, report both in terms of pixels and in terms of physical units (e.g. millimeter) by scaling based on the image scale.

    Note 2: One method of computing the VSG size is given in Eqn. 7.2. Other estimations of the VSG size may be more appropriate, depending on the strain caluclation method used in the DIC software.

  - Post-filtering of strains (spatial and/or temporal), if applied

- Noise-Floor and Bias of QOIs

  Note 1: For 2D-DIC, bias caused by out-of-plane motion should be reported.

  Note 2: There are many factors to consider when evaluating the noise floor, and many possible approaches, as described in Sec. 5.4.2. For reporting purposes, state what method was used, and report the noise-floor value.

6.2.2 Recommended

- DIC Software Package Version Number
- Calibration parameters, such as the following list. Note that models for calibration parameters are software-specific. The parameters listed here represent one particular model; relevant parameters for the selected model used should be reported.
  - Model number and serial number of calibration target used. (This information is useful for traceability and to elucidate any errors in measurements that may be associated with a specific, physical calibration target.)
  - Image Center

    Note 1: Report for both cameras if using stereo-DIC.

  - Focal Length

    Note 1: Report for both cameras if using stereo-DIC.

  - Lens Distortion Correction Model and Parameters
  - Stereo-Angle

    Note 1: Applicable for stereo-DIC; not applicable for 2D-DIC.

  - Distance between Cameras

    Note 1: Applicable for stereo-DIC; not applicable for 2D-DIC.

  - Calibration Quality Metric(s)

7 — Glossary and Acronyms

7.1 Acronyms

DIC: Digital Image Correlation

DOF: Depth-of-Field

FOV: Field-of-View

iDICs: International Digital Image Correlation Society

QOI: Quantity-of-Interest

ROI: Region-of-Interest

SOD: Stand-Off Distance

VSG: Virtual Strain Gauge

7.2 Glossary

Calibration Score: The residual of the bundle adjustment optimization process used to calibrate a DIC system.

Calibration Target: An object with features of specified size and/or spacing, used to calibrate the DIC system, i.e. determine intrinsic parameters (e.g. image scale, focal length, image center, lens distortions) and (for stereo-DIC) extrinsic parameters (e.g. stereo-angle, distance between cameras, distance from cameras to object).

Note 1: Calibration targets are often specific to DIC software packages. Some common types include: (1) a flat plate with circles or dots in a grid with known center-to-center dot spacing, which is often referred to as a "dot-grid calibration target"; (2) a plate with grooves or risers, so that dots are on multiple levels; (3) a plate with a checkerboard pattern.

Note 2: The calibration target should not be confused for a resolution target used to determine the optical resolution of the imaging system.

Data Filtering: Any further post-processing of the results to spatially or temporally filter the DIC results (could include a Gaussian filter, median filter, etc.)

Data Point: A point at which DIC results (displacements, strains, etc.) are reported. Data points are typically reported at the center of subsets in local DIC and at the nodes of the mesh in global DIC. See Fig. 1.2.

Digital Image Correlation: Within the scope of this guide, Digital Image Correlation (DIC) is an optically-based technique used to measure the evolving full-field 2D or 3D displacements on the surface of a test piece, throughout a mechanical test of a material or structure.

Note 1: *2D-DIC* refers to the measurement of displacements in only two directions on the surface of the test piece, where one camera is oriented perpendicularly to a planar test piece.

Note 2: *Stereo-DIC* refers to the measurement of shape and displacements in three directions on the surface of the test piece, by using two (or more) cameras oriented at different angles. Stereo-DIC is sometimes called 3D-DIC, but should not be confused with volumetric-DIC, which provides shape and displacement measurements throughout the volume of the test piece.

Depth-of-Field (DOF) [mm]: The distance, along the optical axis, between the nearest and the farthest objects that are in acceptably sharp focus in an image. See Fig. 1.1.

Dynamic Range, Detector [counts or gray levels]: Number of bits of the analog to digital converter of a camera detector (e.g. 8-bit).

Dynamic Range, Image [counts or gray levels]: Range of gray levels contained in the image data. This can be graphically viewed in the image histogram. The image dynamic range is less than or equal to the detector dynamic range.

Element (Global DIC): Sub-part of the global DIC mesh (in the topological sense of the Finite Element Method).

Element Size, $L_{element}$ [pixel] (Global DIC): Characteristic length of the element (for global DIC) in the reference image.

Note 1: Elements are typically triangular or quadrilateral. Because the element shape can be irregular and can vary across the ROI, the characteristic length of the element is typically the average side length of the element.

Note 2: Since element size may vary across the ROI, report the average and standard deviation, or the average and minimum/maximum, and/or provide an image showing the finite-element mesh.

Epipolar Error [pixel]: The distance between the location of a data point, as determined by cross-correlation of a pair of images from the two cameras of a stereo-DIC system, and the epipolar line.

Note 1: Depending on the DIC software, the epipolar error may also be called projection error, three-dimensional residuum, intersection error, or correlation deviation.

Note 2: The epipolar line is determined by the extrinsic parameters of the stereo-camera calibration (i.e. stereo-angle, distance between two cameras). For more information on epipolar geometry, refer to [1, Sec. 4.2 (Three-Dimensional Computer Vision)].

Field-of-View (FOV) [mm × mm]: The region of space projected through a lens system onto a camera detector. See Fig. 1.1 and Fig. 1.2.

Global DIC Method: A category of DIC methods in which the full image ROI is represented using a global basis, for example, via a finite element formulation, and the full image domain is analyzed together to seek the unknown deformation field.

Gray Level [counts]: The image intensity recorded by the image acquisition system, expressed as the number of counts of the digitizer.

Note 1: This value is proportional to the measured light intensity, but typically has no absolute calibrated relationship to the measured intensity. For DIC, this lack of calibration is acceptable, because the image is used for tracking the object motion, rather than measuring the light intensity at points on the object.

Note 2: Usually the number of counts is relative to the number of bits (quantization level) in the imaging analog-to-digital converter.

Gray Level Residual [counts] (Global DIC): Pixel-wise gray level difference between the image in the reference configuration and the image in the deformed configuration corrected by the measured displacement.

Note 1: The SSD (Sum of Squared Differences) of the gray level residual over the image ROI is generally the matching criterion that is minimized in global DIC.

Image Data: Recorded "images" of a test piece containing encoded information related to the displacement field including displacement gradients, nearly always a 2D or 3D numerical array of "intensity" or gray level data that will be used for correlation.

Image Filtering: Any type of image data processing done to modify the gray level values of the pixels, most often a smoothing operation.

Note 1: *Analog Image Filtering* refers to filtering that is done in an analog fashion by modifying the physical optical system, e.g. with a blur filter assembled on the camera detector or by defocusing the lens.

Note 2: *Digital Image Filtering* refers to filtering that is done in a digital fashion as a post-processing step after the image has been acquired, e.g. a Gaussian filter.

Image Noise [counts or gray levels or percent of dynamic range]: Pixel-wise acquisition noise of the imaging system. This often varies depending on pixel intensity, camera temperature and optical intensity.

Image Scale [pixel/mm]: Number of optical elements (pixels) used to record an image of a region of physical length. The image scale can be used to convert from the image pixel size to physical units (e.g. meter).

Note 1: The image scale varies with position in an image. In 2D-DIC, with a single camera perpendicular to the test piece, the variation tends to be small, since the variation is the result of lens distortions. In stereo-DIC, where the cameras are angled with respect to the surface of interest, the variation in image scale is much larger. This is the result of a combination of the lens distortions and the perspective effect (which is reversed in the left and right images). For stereo-DIC systems, the average image scale of the ROI shall be reported.

Image Size [pixel × pixel]: Total number of pixels contained in an image, typically reported as the width by height of the detector array in pixels.

Integrated-DIC (IDIC): A global DIC method in which the sought displacement fields are mechanically admissible (i.e. constrained by a mechanical condition such as an analytical equation).

Interpolant: Interpolation function used to calculate the subpixel changes within the subset shape function (in the case of local DIC methods) or element shape function (in the case of global DIC methods) transformation subject to the matching criteria during the correlation calculation [1, Sec. 5.6.1 and Sec. 10.2.3.2], [5, 6].

Matching Criterion: Mathematical formulation used to calculate the quality metric of the calculated displacement field based on the underlying image data [1, Sec. 5.4], [8, 10]. Also commonly referred to as "correlation criterion" or "cost function".

Note 1: Common matching criteria include, but are not limited to, sum of square differences (SSD), normalized sum of square differences (NSSD), zero-normalized sum of square differences (ZNSSD) and cross-correlation (CC).

Mesh, Digital Image Correlation (Global DIC): A subdivision of the image ROI into elements.

Node (Global DIC): Nodal point in the global DIC finite element mesh; or sampling measurement points in the global DIC method.

Noise-Floor: [See Resolution of a Quantity-of-Interest.]

Pattern Feature Size [pixel]: Characteristic length (e.g. diameter) of DIC pattern features in the image data, reported in terms of pixels.

Note 1: For DIC patterns that consist of primarily circular features (i.e. speckles), the pattern feature size is sometimes referred to as the "speckle size."

Note 2: If a range of feature sizes exist in the image, the mean size and an indication of the distribution of sizes (e.g. minimum and maximum, or standard deviation) should be reported.

Note 3: Physical size of the features can be calculated by dividing by the image scale.

Note 4: The spatial frequency of the pattern can be determined as the inverse of the pattern feature size (e.g. 1/(pattern feature size)).

Pixel: Region over which the image data is averaged and quantized. There is a resulting gray level or number of counts at each pixel relative to some underlying input, usually optical intensity.

Quantity-of-Interest (QOI): An attribute or property of a test piece that may be distinguished qualitatively and determined quantitatively [64], which a person seeks to characterize by performing a particular test.

Note 1: QOIs may be both direct measurements or derived quantities. With respect to DIC, common QOIs are shape, curvature, displacement, velocity, acceleration, strain, strain-rate, etc.

Quantization Level [bits]: Number of bits used to record the gray level at each pixel. This may be light intensity for optical images, X-ray density for computed tomography, or any other information encoded as image contrast (image data). (A height map in an atomic force microscope is an example of a different type of "image data".)

Region-of-Interest (ROI) of the Test Piece [mm × mm]: The portion of surface of the test piece that is used for analysis. See Fig. 1.2.

Note 1: The term "area-of-interest" is sometimes used interchangeably with the term "region-of-interest."

Note 2: The region may be of any arbitrary shape, and may change shape in consecutive images.

Note 3: The term "region-of-interest" can refer to either a portion of the test piece or the corresponding portion of an image, and context typically is sufficient to distinguish between the two demarcations.

Region-of-Interest (ROI) of the Image [pixel × pixel]: The portion of the image corresponding to the region-of-interest of the test piece. See Fig. 1.2.

Note 1: The term "area-of-interest" is sometimes used interchangeably with the term "region-of-interest."

Note 2: All QOIs are measured or derived using the image data that comes from the ROI of the image.

Note 3: The term "region-of-interest" can refer to either a portion of the test piece or the corresponding portion of an image, and context typically is sufficient to distinguish between the two demarcations.

Regularization (Global DIC): Technique used to diminish random errors in global DIC by adding an additional penalty term to the DIC matching criterion.

Resolution, Optical [line pair / mm]: The ability of an imaging system to resolve detail in the object being imaged.

Note 1: Optical resolution is typically measured from images of a resolution target.

Resolution, Spatial [pixel]: The minimum distance between two localized features that can be independently resolved.

Note 1: This definition might be counter intuitive, in that a smaller resolution value is desireable, whereas a larger resolution value is generally less desirable. These trends are opposite those of image size and optical resolution.

Note 2: For the current edition of this guide, the concept of spatial resolution is defined as above; however, a unified method to determine the spatial resolution of DIC measurements is a current topic of interest for iDICs, and iDICs is actively exploring this concept in more detail.

Resolution Target: An object with features of specified width and/or spacing, used to determine the optical resolution of an imaging system.

Note 1: Two common resolution targets are the 1951 USAF resolution target or the Siemens star, which can be purchased from major optics companies. See https://en.wikipedia.org/wiki/1951_USAF_resolution_test_chart and https://en.wikipedia.org/wiki/Siemens_star for more information.

Note 2: The resolution target should not be confused for a calibration target used to calibrate a DIC system.

Resolution of a Quantity-of-Interest: The threshold value of a QOI below which measurements are indistinguishable from noise, and above which measurements are significant.

Note 1: The phrase "Resolution of a QOI" is used interchangeably with the phrase "noise-floor" in this guide.

Note 2: The noise-floor is typically defined as a multiple of the standard deviation (either spatial or temporal) of the QOI computed under conditions in which the QOI should be zero.

Note 3: The noise-floor reflects only the random variance error of the QOI, and does not reflect any systematic bias errors that may be present in the QOI. See Sec. 5.4 for more information on variance versus bias errors.

Shape Function, Element (Global DIC): Interpolation used to describe the displacement field within an element when using global DIC methods.

Shape Function, Strain: Analytic equation that is fit, in a least-squares sense, to the displacement data within the strain window. Strains are computed from the derivatives of this equation.

Note 1: The strain shape function should not be confused with the subset shape function or the element shape function for global DIC.

Note 2: Not all methods of computing strain invoke a strain shape function.

Shape Function, Subset: Equation used to describe the displacement field within a subset [1, Sec. 5.3], [6, 7].

Note 1: Affine (linear) is the most common subset shape function, but higher ordered implementations are also used.

Note 2: The subset shape function should not be confused with the strain shape function or the element shape function for global DIC.

Stand-Off Distance [m]: The distance between the aperture of the lens and the test piece. See Fig. 1.1.

Note 1: Stand-Off Distance is also often called "Working Distance".

Stereo-Angle [degree]: In a stereo-DIC system, the included angle between the optical axis of each of the two camera systems (i.e. camera and lens). See Fig. 1.1.

Stereo-Plane: In a stereo-DIC system, the plane formed by the optical axes of the two camera systems (i.e. camera and lens). See Fig. 1.1.

Step Size, L_{step} [pixel]: The spacing of pixel grid points at which the subset displacements are calculated. That is, there will be a displacement solution at every step in the ROI. See Fig. 1.2.

Note 1: The step size is also sometimes reported as overlap, i.e. how much two neighboring subsets overlap when the step size is smaller than the subset size. The overlap, $L_{overlap}$, is defined as a percentage of the subset size, L_{subset}, in Eqn. 7.1.

$$L_{overlap} = \left(\frac{L_{subset} - L_{step}}{L_{subset}} \right) 100 \tag{7.1}$$

Note 2: While in local DIC, subsets can overlap, for global DIC, elements are continuous with no overlap. Therefore, only the element size is needed to characterize the finite-element mesh, and there is no equivalent term for step size in global DIC.

Subset: Portion of the image that is used to calculate one 3D coordinate value, or one displacement value in local DIC. See Fig. 1.2.

Note 1: Center point displacement is commonly reported, although other parameters may be available via the subset shape function.

Subset Size, L_{subset} [pixel]: Length of the subset in the reference image. See Fig. 1.2.

Note 1: Subsets are typically square or circular (in the reference image), and thus a single length is sufficient to define the subset size. Some software, however, permits rectangular subsets; in this case, dimensions of both sides of the rectangle should be given to define the subset size.

Virtual Strain Gauge (VSG): The local region of the image that affects the strain value at a specific location.

Note 1: The VSG is analogous to — but not exactly equal to — the physical area that a physical strain gauge would cover.

Virtual Strain Gauge Size, L_{VSG} [pixel]: Characteristic length of the virtual strain gauge.

Note 1: Virtual strain gauges are typically square, circular, or hexagonal, and the size of the VSG is given by the characteristic length of the VSG (i.e. one side of the square, the diameter of the circle, or the effective diameter of the hexagon). The VSG size is specified in terms of the number of pixels that span the characteristic length of the VSG.

Note 2: The size of the VSG depends on the strain calculation method and user-defined parameters such as step size, subset size, strain window, filter window, strain shape function, weighting functions, and subset shape function. An estimate for the size of the VSG, if $L_{window} > 0$, is given by Eqn. 7.2, where L_{window} is the window size (of either the strain window or of the filter window), L_{step} is the step size, and L_{subset} is the subset size.

$$L_{VSG} = (L_{window} - 1)\, L_{step} + L_{subset} \tag{7.2}$$

Note 3: To determine the VSG size in terms of physical units, the VSG size must be divided by the average image scale.

Note 4: For global DIC, the size of the VSG is less straightforward to estimate or compare to the size of a physical strain gauge. Users are advised to use caution when comparing the DIC strains to results from a physical strain gauge. However, in the case local strains are computed through a VSG in an identical fashion on an identical mesh between FE-based global DIC and a finite-element analysis (FEA), strains between global DIC and FEA results can be directly compared.

Weighting Function: Mathematical device used to give some elements more influence on a result than other elements, based on the spatial location of the elements.

Note 1: Common weighting functions are square or uniform (which weights all elements equally) or Gaussian (which weights elements closer to the center point of interest more heavily than elements farther from the center point of interest).

Note 2: A *subset weighting function* is used to weight the intensities of the pixels contained within the subset when performing subset matching.

Note 3: A *strain weighting function* is used to weight the displacement data points within the strain window when computing strain.

Note 4: A *filter weighting function* is used to weight the data within a filter window when applying a spatial data filter.

Window, Filter: Local region of the ROI of the image, containing a finite number of data points, that is used for local spatial filters of DIC data. See Fig. 1.2.

Note 1: See Window Size for information about the filter window size.

Window, Strain: Local region of the ROI of the image, containing a finite number of data points, that is used to calculate strain. See Fig. 1.2.

Note 1: Not all methods of computing strain invoke a strain window.

Note 2: See Window Size for information about the strain window size.

Window Size, L_{window} [data point]: Characteristic length of a local region of data points (e.g. a filter window or a strain window). See Fig. 1.2.

Note 1: Strain and filter windows are typically square, circular, or hexagonal, and the size of the window is given by the characteristic length of the window (i.e. one side of the square, the diameter of the circle, or the effective diameter of the hexagon). The window size is specified in terms of the number of data points that span the characteristic length of the window. Windows are typically symmetric and centered at a data point; thus, window sizes are typically odd integers.

Note 2: The window size in terms of pixels, L^*_{window}, is given by Eqn. 7.3, where L_{window} is the window size in terms of data points, and L_{step} is the step size.

$$L^*_{window} = (L_{window} - 1)\, L_{step} \tag{7.3}$$

Note 3: To determine the window size in terms of physical units, the window size in terms of pixels must be divided by the average image scale.

Working Volume [mm^3]: In stereo-DIC, the intersection of the depth-of-field of both cameras. See Fig. 1.1.

Bibliography

The references contained in this bibliography are provided for further reading on select topics covered in the guide. This list should not be presumed as comprehensive or consummate; additional (potentially better) references may exist, regarding any of the selected topics. Inclusion of these references in this bibliography should not be taken as endorsement by iDICs of these referenced works or their authors.

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A — Checklist and Flow Chart for DIC Measurements and Analysis

This appendix presents a checklist and flow chart of the main points to consider when designing, executing, and analyzing DIC measurements performed during mechanical testing of a planar test piece. Each of the steps listed in the checklist are expounded upon in the main body of this guide, and the flow chart (Fig. A.1) refers in parentheses to specific sections of the guide.

1. **Design of DIC Measurements (2)**
   - (a) *Measurement Requirements*
     - ☐ QOIs (2.1.1)
     - ☐ ROI (2.1.2)
     - ☐ FOV (2.1.3)
     - ☐ Position Envelope for Hardware (2.1.4)
     - ☐ 2D-DIC vs Stereo-DIC (2.1.5)
     - ☐ Stereo-Angle (2.1.6)
     - ☐ DOF (2.1.7)
     - ☐ Spatial Gradients (2.1.8)
     - ☐ Noise-Floor (2.1.9)
     - ☐ Frame Rate (2.1.10)
     - ☐ Exposure Time (2.1.11)
     - ☐ Synchronization and Triggering (2.1.12)
   - (b) *Equipment Selection*
     - ☐ Camera and Lens (2.2.1)
     - ☐ Mounting Equipment (2.2.2)
     - ☐ Aperture (2.2.3)
     - ☐ Lighting and Exposure (2.2.4)
     - ☐ DIC pattern (2.3)
   - (c) *Mock Test (Optional)*
     - ☐ Test DIC pattern technique on extra test piece(s).

- ☐ Evaluate DIC pattern behavior throughout test.
- ☐ Evaluate lighting/contrast throughout test.
- ☐ Evaluate data synchronization and triggering.

2. **Preparation for the Measurements (3)**

   (a) *Pre-Calibration Routine* (3.1)

   - ☐ Review test procedure (3.1.1).
   - ☐ Check cleanliness of camera detector, lens, and calibration target (3.1.2).
   - ☐ Warm up cameras (3.1.3).
   - ☐ Synchronize cameras to each other and to other data acquisition (3.1.4).
   - ☐ Apply DIC pattern (3.1.5).

   (b) *Pre-Calibration Review of System (3.1.6)*

   - ☐ Position test piece in load frame (3.1.6.1).
   - ☐ Position cameras for desired FOV and image ROI (3.1.6.1).
   - ☐ Verify FOV, focus, DOF (3.1.6.2).
   - ☐ Lock all moving parts of cameras, lenses, and mounting system (3.1.6.3).
   - ☐ Adjust orientation of polarization filters if using cross-polarized light (3.1.6.3).
   - ☐ Review static images (3.1.6.4), looking for:
     - Glare
     - DIC pattern that is too coarse or too fine
     - Defects in applied DIC pattern
     - Out-of-focus regions of the image
     - Poor contrast
     - Non-uniform lighting
     - Overexposed or underexposed regions
     - Dirt, smears, foreign object on lens or camera detector
     - Vibrations or other camera motion
   - ☐ Adjust DIC system until high-quality images are obtained.

   (c) *Calibration (3.2)*

   - ☐ Select calibration target of appropriate size. (3.2.2.1).
   - ☐ Create a clear working space in which to perform calibration (3.2.2.2).
   - ☐ Lock all moving parts of cameras, lenses, and mounting system (3.2.2.2).
   - ☐ Adjust lighting/exposure (3.2.2.3).
   - ☐ Ensure there is uniform contrast and no glare as the calibration target is rotated, tilted, and translated (3.2.2.3).
   - ☐ Acquire calibration images that have well-extracted features in the entire working volume of the optical system (3.2.2.4).
   - ☐ Calibrate the system (3.2.2.5).
   - ☐ Review calibration results (3.2.2.6).
   - ☐ Review calibration parameters (3.2.2.7).

(d) *Post-Calibration Routine (3.3)*

- ☐ Reset system: Position test piece in load frame (if removed for calibration) or reposition stereo-camera system (if moved for calibration) and lock any moving parts (3.3.1.1).
- ☐ Adjust lighting/exposure (3.3.1.2).
- ☐ Acquire static images (3.3.1.3).
- ☐ Review static images (3.3.1.4 and 3.1.6.4), looking for:
  - Glare
  - DIC pattern that is too coarse or too fine
  - Defects in applied DIC pattern
  - Out-of-focus regions of the image
  - Poor contrast
  - Non-uniform lighting
  - Overexposed or underexposed regions
  - Dirt, smears, foreign object on lens or camera detector
  - Vibrations or other camera motion
- ☐ Acquire rigid-body-motion images of test piece for noise-floor analysis (3.3.1.5).
- ☐ Verify calibration (3.3.2).
  - Intrinsic parameters (3.3.2.1)
  - Extrinsic parameters (3.3.2.2)
  - Absolute distances (3.3.2.3)
- ☐ Perform abbreviated noise-floor analysis and ensure the noise-floor is acceptable (3.3.3.1).
- ☐ Look for heat waves (3.3.3.2), system stability (3.3.3.3), and any other lab-specific system verifications (3.3.3.4).

3. **Execution of the Test with DIC Measurements (4)**

- ☐ Verify correct file name, location, and storage capacity for DIC images.
- ☐ Verify that the correct test procedure or macro has been selected.
- ☐ Verify force and other measurements of interest are set to record and are synchronized with DIC images.
- ☐ Verify triggering of load frame and DIC images.
- ☐ Verify that lights are on, exposure is correct, frame rate is correct.

4. **Processing of DIC Images (5)**

- ☐ Select initial correlation and user-defined parameters.
- ☐ Perform initial correlation of images.
- ☐ Re-analyze images using different user-defined parameters. (For example, do a VSG study if strain is the QOI.)
- ☐ Based on results of the different correlations, select a final set of user-defined parameters.
- ☐ Correlate all images using finalized parameters.
- ☐ Quantify variance and bias errors using finalized parameters (5.4).

5. **Reporting Requirements (6)**

- ☐ Justify and document selection of all choices in the test and analysis of DIC data.

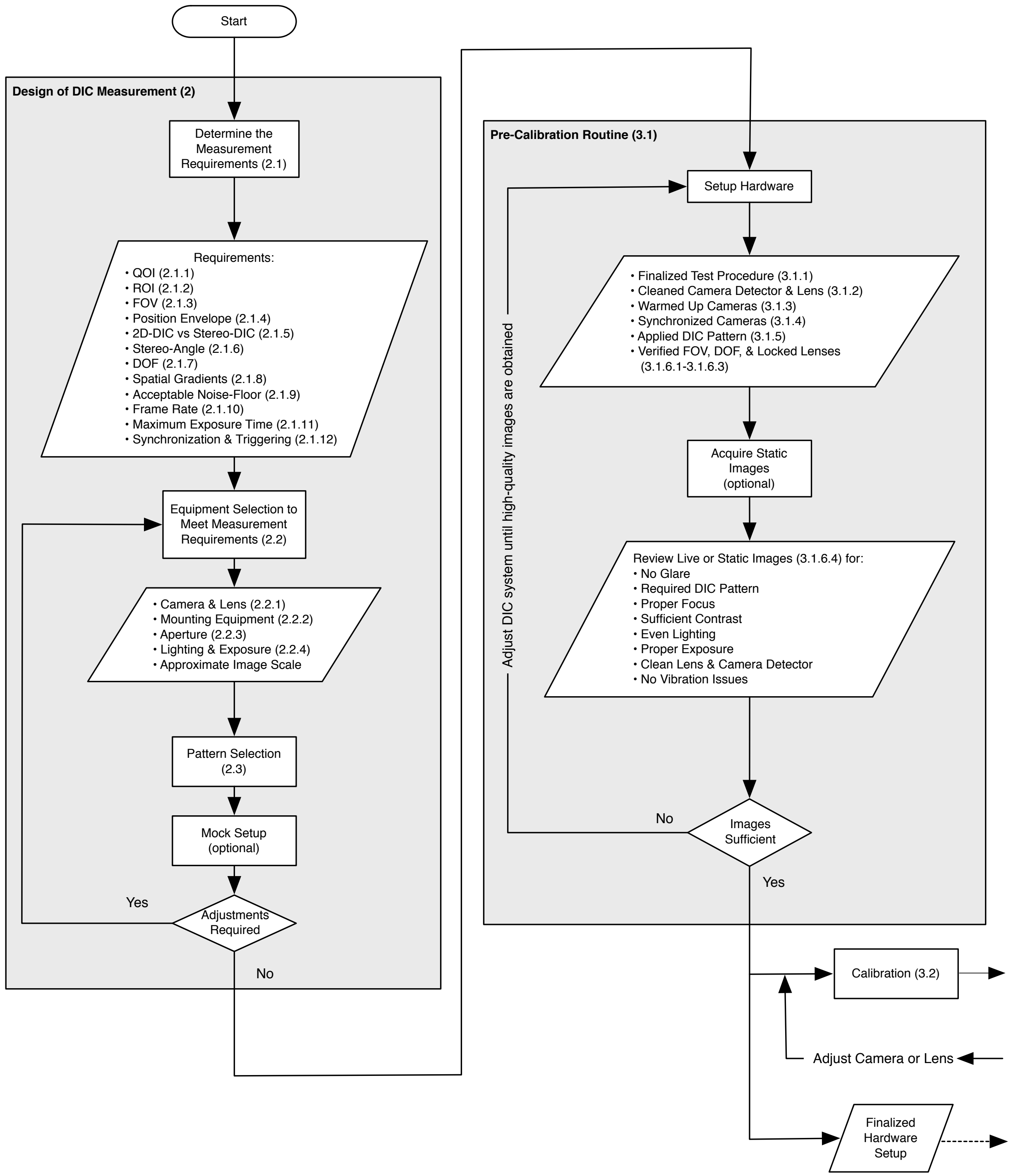

Figure A.1: Flow chart illustrating the main steps involved when conducting DIC measurements in conjunction with mechanical testing of a planar test piece (part 1).

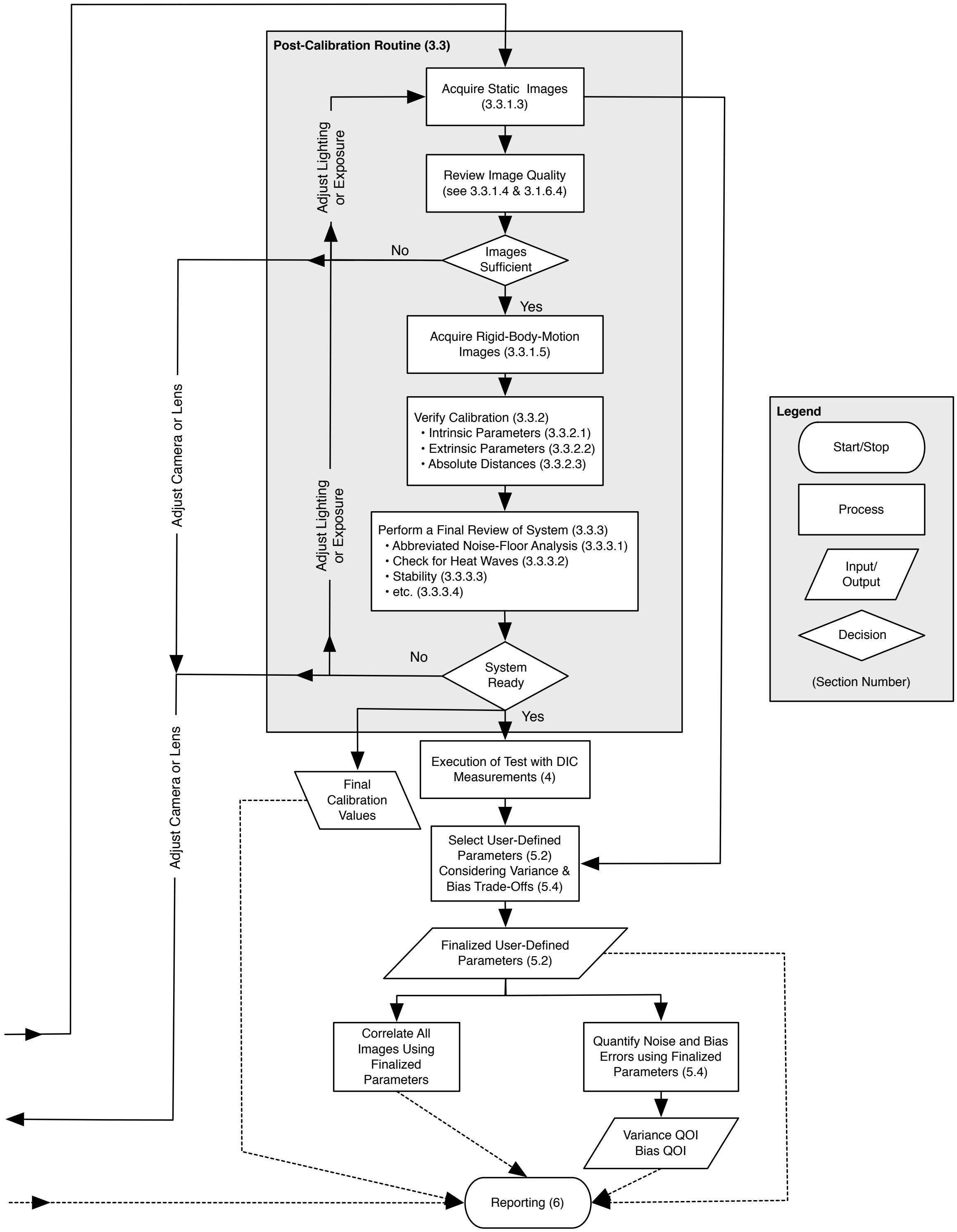

Figure A.2: Flow chart illustrating the main steps involved when conducting DIC measurements in conjunction with mechanical testing of a planar test piece (part 2).

B — Focal Length, Field-of-View, and Stand-Off Distance

Thin lens theory[25,26,27] defines a set of basic equations that may be used to approximate FOV or SOD between the camera(s) and the patterned test piece, for given set of camera and lens hardware. These equations are not exact, due to intricacies of real optical systems that are beyond the scope of the current edition of this guide, but they have proven to be close enough to use for setting up DIC in practical situations. They begin to break down in macro-lens photography situations, and should therefore not be relied upon for high accuracy when the FOV size shrinks to twice the detector size or smaller. In general usage, they are good for determining, for example, which lens from a kit of lenses to use, or for determining the approximate SOD.

In many typical DIC setups, the camera bar is set in a fixed location relative to a test fixture containing a patterned test piece (i.e. a fixed SOD), and it is desirable to calculate the FOV for a given lens, to determine if the ROI on the test piece will be imaged. The characteristic length of the FOV (L_{FOV}) can be closely approximated using the focal length of the lens(es) used (L_{FL}), the distance from the camera(s) to the patterned object (i.e. the SOD, L_{SOD}) and the width of the camera detector(s) (L_{CS}):

$$L_{FOV} = L_{CS}\left(\frac{L_{SOD} - L_{FL}}{L_{FL}}\right) \tag{B.1}$$

Online calculators[28]are available to quickly solve for the FOV, and extend the formula to account for rectangular detectors. Conversely, in some setups the required FOV is fixed by the test piece, and the lens focal length is fixed by the hardware on hand, but the distance to the test piece (i.e. SOD) may be adjusted by moving the camera bar. In this case, rearranging equation B.1 gives:

$$L_{SOD} = L_{FL}\left(\frac{L_{FOV}}{L_{CS}} + 1\right) \tag{B.2}$$

The camera detector width is usually found in manufacturer specifications for the camera hardware. Sometimes, pixel size (typically in microns) is used instead. In the latter case, L_{CS} is simply the pixel size multiplied by the number of pixels across the image. This is also true in cases where a cropped

[25] *Thin Lenses* by Prof. Richard Fizpatrick: `http://farside.ph.utexas.edu/teaching/3021/lectures/node140.html`
[26] *Lens (optics): Imaging properties* on Wikipedia: `https://en.wikipedia.org/wiki/Lens_(optics)#Imaging_properties`
[27] *Lens Focal Length Calculator* by Iacopo Giangrandi: `http://www.giangrandi.ch/optics/focalcalc/focalcalc.shtml`
[28] *Calculator for field-of-view (FOV) of a Camera and Lens* by Wayne Fulton: http://www.scantips.com/lights/fieldofview.html

Table B.1: Photron MH4 stereo pair at 1.52 m (60 in) SOD ($L_{SOD} = 1.52$ m)

Focal Length (L_{FL})	**FOV Width** (L_{FOV})
6 mm	1.22 m (48 in)
8.5 mm	0.86 m (34 in)
12 mm	0.61 m (24 in)

image, less than the full image size, is being used: simply multiply the width of the cropped image in pixels by the physical pixel size to obtain L_{CS}. If only the detector width is in the specifications, it may be necessary to first calculate the pixel size by dividing L_{CS} by the full frame pixel width. Note that "binning" allowed by some cameras does not reduce L_{CS}, because it still utilizes the full detector, but combines data from multiple pixels to create a lower pixel count image (unless binning is used in addition to cropping of the image).

A practical use of Eqn. B.1 and Eqn. B.2 is building quick-reference tables for fields-of-view or SODs for a given set of hardware. For example, consider a Photron MH4 hardware kit containing two cameras, a stereo mounting bar, and several fixed focal length (non-zoom) lenses. In this case, the stereo mounting hardware fixes the stereo-angle, which effectively locks the SOD at $L_{SOD} = 1.52$ m (60 in). In the kit are 6, 8.5, and 12 mm lenses. A chart can be drawn up for the available measurement widths achieved by switching lenses, using Eqn. B.1 and a camera detector width of $L_{CS} = 4.80$ mm, reduced from the full detector width of 5.12 mm for these cameras to account for stereo overlap. The resulting table is shown in Table B.1. Similar measurement width tables may be formed for other camera kits, to be used as quick-reference guides. When the FOV is fixed (constrained by the test piece size in a universal test machine, for instance), Eqn. B.2 may be used to create quick-reference tables of working distance required to use various lenses in a kit or being considered for purchase.

Another practical outcome of Eqn. B.1 and Eqn. B.2 is that the FOV and SOD for a specific lens and camera can be memorized, and then the linearity of lenses can be invoked to quickly calculate the FOV and SOD for other lenses. For example, one could memorize that the widely used 2/3" format camera detector, with an 8 mm focal length lens, has a FOV that is slightly less wide than the SOD. Therefore, with a 50 mm lens (which has a focal length about 6X longer than an 8 mm lens), the required working distance is approximately 6X the desired FOV.

C — Global DIC

C.1 Introduction: What is global DIC?

As explained in the main text of this guide, DIC (both local and global methods) uses an interpolant of the displacement field to perform correlation-based matching to aid in encompassing the effects of strain and perspective. The main difference between local and global DIC methods is the region of the image considered for the interpolation and the corresponding registration.

As described, the local or subset-based DIC method applies the correlation interpolant to a set of independent smaller subsets (interrogation windows) of the images, composed of a limited number of pixels. The resulting displacements are only defined over a finite set of interrogation points (typically centered in the subset), usually distributed over a regular grid built on the pixels. The lack of interaction between these subsets is the reason for the term "local method". Determining a displacement between these points (e.g. for comparison with simulation results) requires subsequent interpolation.

In contrast, a global DIC method performs on an *a priori* chosen interpolant based on a set of shape functions to represent and solve the displacement field over the entire Region Of Interest (ROI) of the image, and hence the term global. The displacement is then defined anywhere inside the ROI of the test piece. This approach allows the user to prescribe an *a priori* condition on the kinematic fields such as continuity. Currently, the most common and well known global DIC method relies on a Finite Element description of the kinematics throughout the ROI of the test piece [66, 72, 104, 106] (see Fig. C.1). This approach is referred to as Finite Element-based Global DIC (FE-based Global DIC). The user has then to define a measurement mesh that can either be built or imported from a simulation model. The degrees of freedom retrieved by the DIC software simply become the nodal displacements to be assessed. It is worth mentioning that the measured displacement is known everywhere within the mesh from the FE shape functions.

As in local DIC, a code analyzes a user-defined region-of-interest (ROI) within the images, which contains a set of interrogation, or measurement, points. In finite-element based global DIC, interrogation points are the nodes of a finite element mesh. The mesh element size defines the spacing between these interrogation points. The elements are numerically correlated from the reference image (before motion/deformation) to each subsequent image (during motion/deformation). This correlation is performed by first approximating the pattern in each element using an interpolant function, and then allowing that function to deform from the reference image based on an element shape function. A gray level residual (difference between reference configuration and deformed configuration gray levels) is minimized to match each element in the reference image with the corresponding element in the deformed images, while conserving continuity from the FE mesh. In stereo-DIC, the gray level residuals, along with the parameters of the stereo-system calibration, are also used to match elements from one of the cameras to the other camera. The result of the correlation is the measured coordinates of each node of

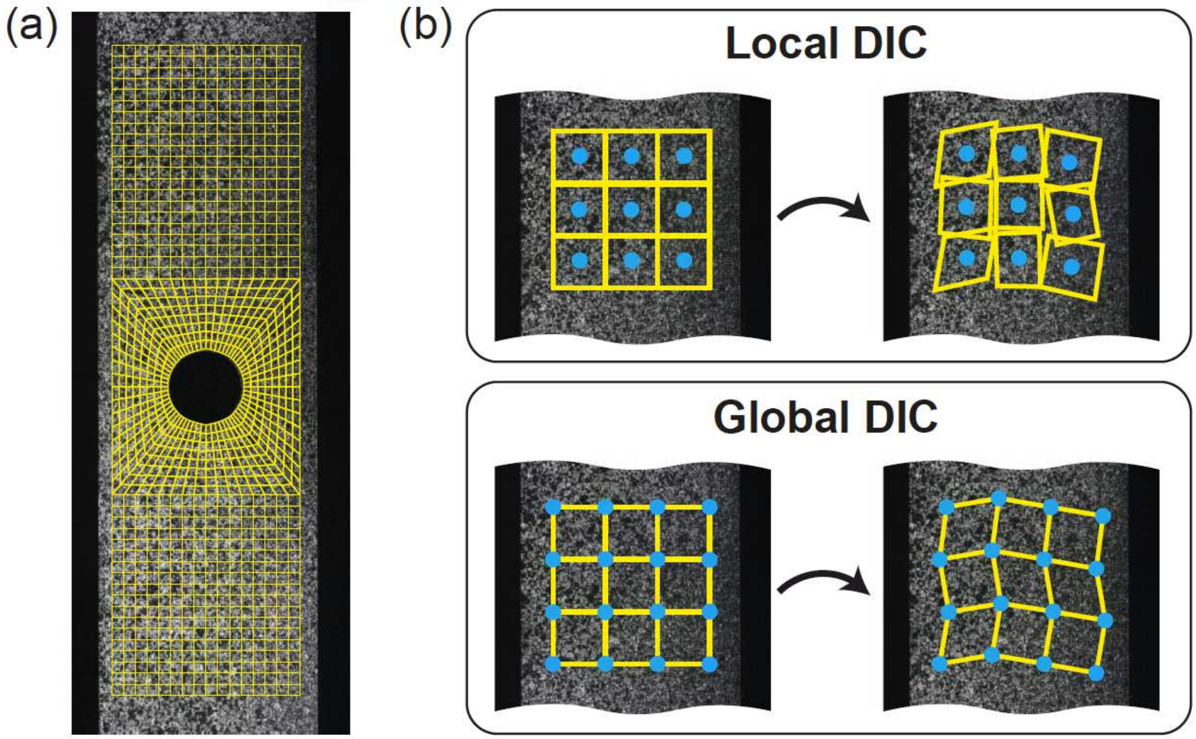

Figure C.1: (a) A representative FE-mesh over the whole ROI in the FE-based Global DIC. (b) Comparison between local DIC and global DIC.

the mesh.

Alternative global DIC methods also exist in the literature:

- Techniques exist to automatically select each element's shape function to achieve the smallest error possible per degree of freedom, regardless of the original mesh [110–112].
- Some approaches involve imposing the continuity of the strain field in the whole ROI of the test piece (for example by using splines [71, 88], or a spectral approach [81, 108], or adding global kinematic constraints as additional penalties onto the correlation cost function [113, 115]).
- For specific behaviors and/or geometries, analytical closed form solutions of the displacement field may be enforced. In this case (referred to as Integrated DIC), if the assumptions are correct, the user may additionally identify some constitutive parameters. Known examples include:
  - beams [77],
  - cracks [102],
  - rigid body [85],
  - diffusion interface [109],
  - numerically precomputed solutions [79].
- Global versions of DIC might also encompass time in the solution minimization [67].

In this document the term "global DIC" will be used to refer to the FE-based global DIC method, although in general "global DIC" is not limited to the FE-based method. Both 2D and 3D global DIC are considered here, the main difference being the calibration phase (see Sec. C.3.2).

C.2 Why use global or local DIC?

It is to be noted that local and global DIC approaches share a number of commonalities in their construction and their use, for which the reader of this appendix can directly refer to the main body of this guide. Main instances include:

- Measurement requirements: the same rules proposed in Sec. 2.1 of the main body of this guide apply.
- Hardware: the same advice proposed in Sec. 2.2 of the main body of this guide applies.
- Pattern quality: specific cases can arise in the case of small or very deformed FE elements in global DIC, but in general the user should be aware that advice given in Sec. 2.3 of the main body of this guide remains fully valid in global DIC.
- Pre- and post-calibration routine: the same advice proposed in Sec. 3.1 and Sec. 3.3 of the main body of this guide applies (general system set-up and measurement uncertainty best practices).
- Image series preparation and gray level interpolation, for which the same techniques are used in both local and global DIC approaches (Sec. 5.2.1 to 5.2.5 in the main body).

Nevertheless, several factors have to be taken into consideration when selecting the type of DIC method for a given experiment. Some of these factors are more in favor of using a global DIC method:

- (FE-based) Global DIC has the advantage of being a natural counterpart to Finite Element Analysis (FEA). When comparing FEA results with experimental DIC data, it can be difficult to ensure spatial coincidence between these datasets. Using a global DIC method with the FE mesh that has been used in the simulation is a logical solution to this issue, allowing direct "node-to-node" comparison. Moreover, the kinematic fields are directly expressed in the coordinate system and in the unit of the mechanical FE model. It is however to be noted that DIC-measured strain maps can include more noise than FEA results, and that a unified method for strain computation would have to be used before quantitative comparisons (see Sec. C.5.3 of this appendix).
- Global DIC guarantees the kinematic compatibility of the deformation field over the entire ROI and regularization can be further introduced to reduce the measurement noise. For example, because of its natural connection to FEA, global DIC allows imposing a mechanical regularisation in a straightforward way [90, 105], as discussed in Sec. C.4 of this appendix. In this case, Global DIC can be less affected by local image contamination (for instance, in the case of a degrading DIC pattern, a local image saturation, or if visible particles move between the lens and the test piece), and can fill the missing local information from adjacent regions, while Local DIC loses local elements/subsets where the image quality is poor [114].
- In general, global DIC allows the user to measure very complex geometry (right angles, ribs, holes) where the user can provide a very close initialization of the shape of the measured test piece. It is often possible to measure displacements up to the edges of the ROI, which is useful if the user wants to limit the number of "lost" elements.

- The method provides direct access to the gray level residuals for each evaluation point within the ROI of the test piece. These residuals can be plotted easily. The residuals may indicate where the kinematics is not rich enough to describe the deformation of the test piece from the images. For instance, one can imagine the situation where a crack initiates during the test. The discontinuity of the displacement field will result in strong concentrated residuals around the crack path. This is less robust when trying to observe correlation error maps at the pixel scale in local DIC packages.
- Although not in the scope of this document, less generic global DIC methods (i.e. integrated-DIC) allow the user to very closely match the anticipated test kinematics (beam, crack, etc.). This can help regularize the observed kinematics in the case of a poor signal to noise ratio [74], or to identify directly simulation parameters without using a post-processing step [75, 79, 80, 102].

Conversely, local DIC methods have their own advantages:

- Local DIC is very generic and does not need to input any geometric features of the test piece. This enables the processing of image data for users who are using DIC even in cases where the measurement is not to be compared to (or regularized by) any mechanical model.
- Local DIC does not enforce displacement continuity within the measurement region, which can be important to some users in the case of studying crack opening for instance. Global DIC methods in these cases (remeshing, enrichment functions, integrated DIC) are proven to function well but are less straightforward and do not currently exist in commercial packages. Local DIC methods, to solve for cracks, also introduce additional operations such as subset-splitting to achieve higher accuracy.
- The local DIC method is parallelizable by nature; however, the global DIC method is not as easily parallelized (although the FE parallelization scheme is an option [86, 101]). Therefore, to track large-size images with fine spatial resolutions, local DIC can allow faster processing.
- In order to use an existing mesh for a displacement field measurement, Global DIC methods often rely on a self-calibration procedure (see Sec. C.3.2.2.2) to be used. This procedure requires the mesh to be aligned to the image in order to use the piece itself as a calibration object. Fitting an existing mesh to an image requires the ability to accurately locate fiducials (e.g., sharp angles or corners) that can be observed both in the images and the mesh (or its environment) to initialize this self-calibration procedure. If it is not possible to ensure this image/mesh correspondence, then the use of global DIC is impractical.

C.3 Global DIC Practical Implications

C.3.1 Mesh Definition and Positioning

Using a mesh for a displacement field measurement has practical implications when defining the ROI of the test piece. Two situations can be encountered:

- The mesh can be defined directly on the image, in which case it is not derived from a simulation and the mesh generation is done in the similar way to the interrogation point grid generated in the local DIC method. However, in the global DIC method the node points are selected;

- The mesh is loaded from a simulation file, and has to be positioned in the images in order to select either a group of surface elements that will constitute the ROI of the test piece, or a group of pixels per image that will constitute the ROI of the images.

The first kind of situation is very similar to the operations performed in a local DIC package: a regular grid is positioned on a reference image, and will be used as the ROI of this image. In this situation, no special positioning technique has to be used. The grid geometric parameters (especially the space between nodes) can be chosen independently from the simulation. After the DIC computation, the result is provided on this grid, and then has to be exported by the user to the simulation reference system if a comparison to simulation results is to be made.

The second method allows the user to take advantage of an existing mesh, in order to perform a more direct comparison to simulation data when the measurement would have been performed. It also allows the use of mesh-based multi-camera measurement techniques in a direct fashion. To proceed with the calibration and measurement steps, the user will have to ensure a geometric correspondence between the mesh reference system and the image content (see Sec. C.3.2 on 2D and 3D calibration).

Caution C.1 — Element Size

The consequence of this procedure is that the element size (in pixels) cannot be known precisely before this step is taken. In this context, the element size can be estimated at first, and fully validated only when the reference images have been taken. The user can then ask for a DIC mesh adaptation (refinement or coarsening) if it does not fit their expectations about element size. To know more about mesh size validation, please refer to Sec. C.4.2 of this appendix.

C.3.2 Calibration

Commercial packages have different calibration strategies, depending on the mesh definition options that were presented in the previous section. Options described here are available in commercial packages, but alternative routes exist.

C.3.2.1 2D Global DIC

C.3.2.1.1 New Mesh

In the case the user does not provide a pre-existing mesh, the user has to define one on the reference image. In this case, the DIC program builds its own (generally structured) mesh from the definition of a region of interest (ROI) in one image, similarly to what is done in local DIC. The procedure for calibrating a single camera in a global DIC program is very similar to what is described for local DIC in Recommendation 3.5 of the main body of this guide:

- If available, calibrate the camera via a simplified target calibration procedure, which allows correction for optical distortions.

- If not, the user can input a pixel-to-meter ratio that has been calculated based on fiducials of the image or (ideally) a resolution target.

C.3.2.1.2 Pre-Exising Mesh

In the case of using a pre-existing mesh, calibration for a single camera consists of:

- Fitting the mesh to the image via the use of fiducials as described in Sec. C.3.2.2.2.1. This step will allow estimating the camera intrinsic and extrinsic parameters that link the mesh coordinate system with the image coordinate system.
- Possibly correction for distortions separately via a simplified target calibration procedure. It is always advised to correct for optical distortions whenever possible.

Caution C.2 — Mesh Position Uncertainty

In a commercial global DIC software, the mesh positioning uncertainty is on the order of the user's ability to pick a fiducial with a mouse-click (from one pixel to a few pixels depending on the geometry visibility and quality). This should be taken into account when processing the results, possibly by performing user-sensitivity analyses to estimate results variability. Commercial packages use points as fiducials, but some other packages also allow using lines or curves.

Caution C.3 — Planar Assumption of 2D DIC Calibration

When performing 2D DIC calibration with a pre-existing mesh, the user assumes the points of the mesh that will be reprojected are contained within the same plane. If the ROI of the test piece mesh does not satisfy this condition, software packages may not accept to perform the analysis.

C.3.2.2 Stereo Global DIC

C.3.2.2.1 New Mesh: Traditional Calibration Techniques

In the case the user does not provide a pre-existing mesh, the procedure for calibrating a stereo pair in a global DIC program is very similar to what is described for local DIC in Sec. 3.2 of the main body of this guide, with the use of a calibration target. For a two-camera DIC system, the mesh is usually created as a regular grid in the ROI of the primary camera. The mesh coordinate system is created based on an arbitrary origin and orientation, usually set by the first calibration image of the left picture. Good calibration practice follows advice given in Sec. 3.2 of the main body of this guide.

C.3.2.2.2 Pre-Existing Mesh: Self-Calibration

In the case of using a pre-existing mesh for a stereo global DIC system, the alignment procedure described in Sec. C.3.2.2.2.1 is used as initialization for a "self-calibration" procedure.

A stereo calibration consists in identifying a set of cameras' extrinsic and intrinsic parameters. The vast majority of calibration procedures in DIC rely on the use of a calibration target, used to provide a well-known object as a reference to build the stereo reference system (see Sec. 3.2.2 of the main body of this guide). This kind of procedure replaces this calibration object by the test piece itself, which geometry is assumed to be sufficiently well-known to calibrate the cameras (see Sec. C.3.2.2.2.1 for more details).

The full self-calibration process is shown in Fig. C.2 and consists of four steps:

1. Pre-calibration, which aims to initialize the camera model associated with each camera,
2. Camera calibration, which aims to update the camera model in total or in part (e.g. only extrinsic parameters) in a more robust way

3. Shape correction, to update the shape of the finite element model to account for deviations from the nominal geometry when measuring the displacement fields.

4. Possible iteration between the two last steps.

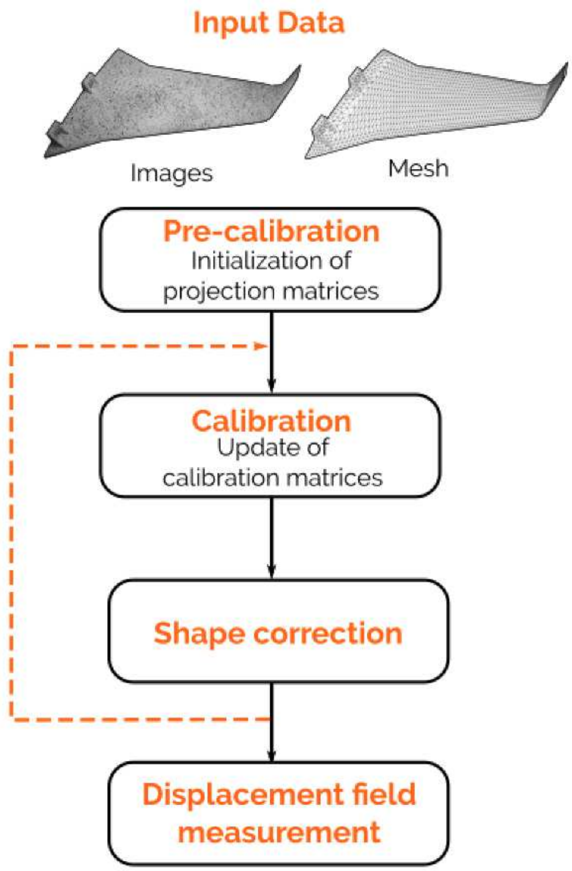

Figure C.2: Diagram summarizing the principle of the self-calibration algorithm, and illustration of the pre-calibration step with matching of 2D image points and 3D model points.

C.3.2.2.2.1 Pre-Calibration: Mesh Alignment

An important step for calibration is aligning the mesh to the images for each camera. Mesh/image correspondence is usually achieved by selecting fiducials that are visible in the image, with known coordinates in the mesh reference system. These fiducials can be either a part of the mesh (specific corner nodes or edges for instance) or elements of the environment with known coordinates with respect to the mesh. To achieve this pre-positioning step, the user has to select these fiducials in a way that they will be positioned in a 3D space encompassing the measurement area (depending on the software); see Fig. C.3. Once this correspondence is found, the mesh surface nodes are projected onto the images and this part of the mesh can be superimposed (see Fig. C.4). Some DIC packages automatically remove elements that are not visible or for which the reprojected surface is too small.

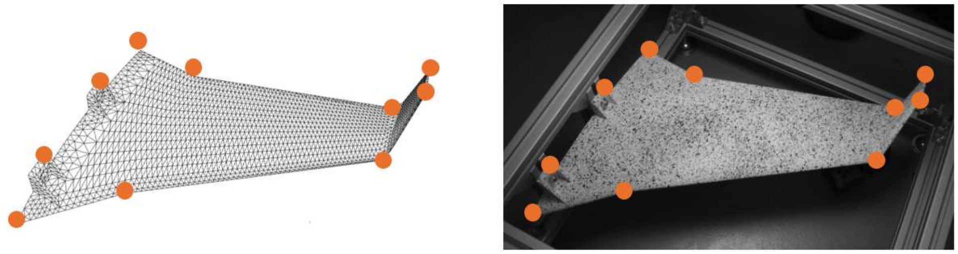

Figure C.3: Example of fiducial selection on the FE mesh (left) and in one of the reference images (right). Fiducials have to be well distributed in the 3D space in order to provide a good first approximation of the mesh/image alignment.

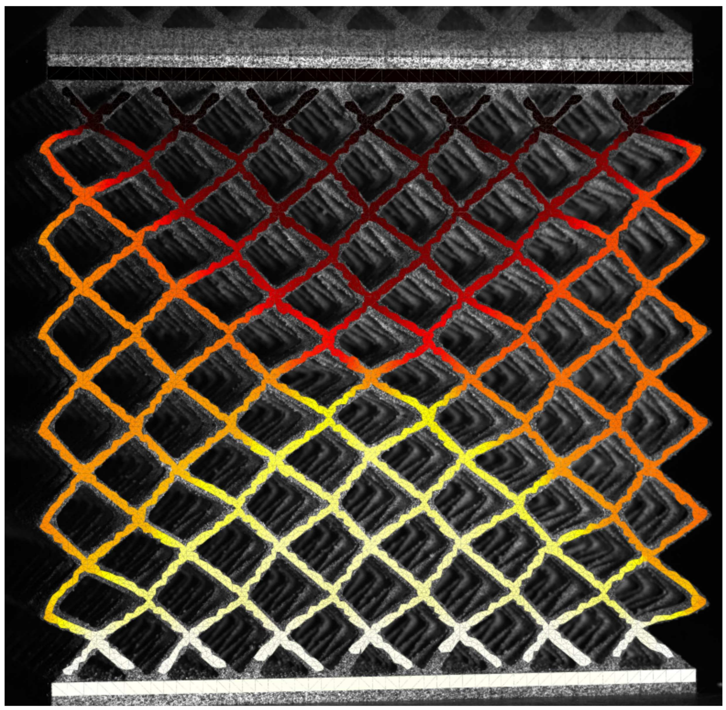

Figure C.4: A representative global DIC FE mesh over complex geometry ("Lattice structure under compression, courtesy of Ludovic Barrière, IRT Saint-Exupéry")

Tip C.1 — Number of Fiducials

Eight to ten fiducials are often recommended to ensure that both the translation and rotation of the mesh are aligned with the sample. These fiducials have to be well distributed in the 3D space and in the image to avoid bad conditioning of the inverse problem that solves for these projection matrix terms. It is good practice to prepare the list of fiducials in advance to make sure the calibration step will run smoothly. See Fig. C.3.

Tip C.2 — Fiducials and Calibration Target Images

In the case where the available fiducials do not cover the full ROI of the test piece, it is possible to add calibration target images to account for distortions and help pre-calibrate robustly.

Caution C.4 — Mesh Alignment

The first alignment step of the simulation data to the experimental results is only as good as a mouse click pixel selection. Errors of ± 1 pixel are typical. The mesh positioning step has a direct impact on the displacement measurement, since the measured displacement at the node will directly depend on this node's position in the image. Existing literature does not study this question to the authors' knowledge.

C.3.2.2.2.2 Self-Calibration: Extrinsic and Intrinsic Parameters Determination

The principle of self-calibration is to use the nominal geometry of the component, as defined in the finite element mesh, to position and orient the camera system with respect to the 3D coordinate system of the model. A DIC algorithm then matches all images for each element to compute a residual, and minimizes this residual by searching for optimal extrinsic and/or intrinsic parameters. During this step, it is assumed that the observed geometry matches the FE model shape that was provided in the original mesh, which is to be corrected in the next step.

Caution C.5 — Initialize Calibration Problem

The calibration operation consists in solving an ill-posed inverse problem by an iterative method. In some cases, bad initialization can prevent calibration from converging.

Recommendation

Therefore, it is preferable to initialize the problem with a set of parameters fairly "close" to the final solution to ensure algorithmic robustness. This initialization is determined by the pre-calibration step, which is therefore a crucial step to obtain a robust calibration. When in doubt, refer to the software vendor as algorithm solutions are software-specific.

Tip C.3 — Shape Error

When measuring a part with a shape defect, a tolerance of 1% of the field of view is generally considered acceptable. For instance, if the field of view is 100 mm large, the user may expect that a 1 mm shape error does not have a strong effect on calibration. The user should consult the vendor to understand the capability to overcome the large shape defects during the self-calibration procedure.

C.3.2.2.2.3 Shape Correction

Once the extrinsic and intrinsic parameters are determined and fixed, the FE shape can be corrected. A DIC algorithm then matches all images for each element to compute a residual, and minimizes this residual by searching for optimal nodal positions for all nodes of the ROI of the test piece.

C.3.3 Crack Measurement

When a crack occurs in a displacement field, global DIC tends to show results even for the element intersected by the crack. In local DIC, non-converged subsets (which are intersected by cracks) are often discarded. Recall that the global DIC method enforces continuity which is completely inappropriate when a crack exists. Therefore the measurements in this zone are not usable, but the location of the cracks can then be detected from the resulting gray level residual field[29]. Meshes accounting for the presence of such cracks can be subsequently re-constructed [107] or the kinematic basis of elements passing crack paths can be further enriched [89]. Alternative local DIC approaches introduce subset splitting to solve the same kind of issues.

C.4 User-Defined Parameters

A Finite Element (FE) discretization of the displacement field in the whole region of interest of the image is adopted. The value of the displacement at any point is obtained from the nodal displacements of the element it belongs to and the shape functions. The continuity of the displacement field is thus enforced at any location inside the ROI. As presented in Sec. C.3.1, the user has to generate a mesh and place it onto the image. This mesh can be loaded from FE codes or created by the user. In both cases, the user has to validate the mesh is suited to follow the speckle pattern, which can be done by looking at the parameters discussed in the following sections. It is to be noted that parameter choices have to be further validated with an uncertainty quantification approach.

C.4.1 Element Shape Function Type

Global DIC packages allow the user to pick shape functions for the mesh elements that are used for the measurement (see Fig. C.5). Usually finite element shape functions are the typical choice, since they can be imported from the original FE simulation mesh. DIC computations are usually performed by assembling gray level data from evaluation points contained in each projected element (in 3D DIC) or pixels (in 2D approaches).

Caution C.6 — Shape Function and Element Size

Just like in a FE computation, measuring displacements with higher order (e.g. quadratic) elements allows the description of smooth changes in the displacement/strain field more accurately, but the higher order shape functions also requires solving an inverse problem with more degrees of freedom assuming the element size is constant. The consequence is that higher order elements for instance must encompass more pixels than linear elements to achieve the same uncertainty level (see Sec. C.5.2 for more details about uncertainties).

C.4.2 Element Size

The element size plays a similar role as the subset size in local DIC methods. The element size should be at least of the order of the feature size of the DIC pattern [31]. As the mesh is often imported from a simulation model, it should be emphasized that element size can vary in the ROI of the image.

[29] The processing of gray level "cracks" being a topic by itself, and it will not be treated in this document.

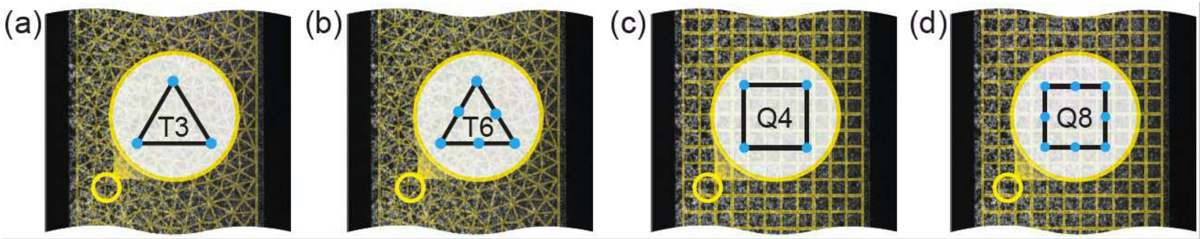

Figure C.5: Examples of Global DIC element shape functions: (a) linear triangle, (b) quadratic triangle, (c) quasi-linear quadrangle, and (d) quadratic quadrangle

Caution C.7 — Element Size and Shape Function

Without mechanical regularization (see Sec. C.4.3), the user will have to make a trade-off between small element sizes to capture very high displacement gradients and high measurement uncertainties that increase with decreasing element sizes. The element size and element shape function type cannot be chosen independently. A higher order element should encompass more pattern features than a linear element, as it requires solving a higher number of degrees of freedom. Rules of thumb described in the main body of the guide for subset size (Sec. 5.2.6) can also be applied here.

Tip C.4 — Shape Function

As global DIC meshes often come from a simulation mesh, a logical approach can be to use the same shape functions in the DIC and in the simulation. Refer to the DIC vendor manual for more information on these matters.

Tip C.5 — Element Size and Number of Features

As with subset-based DIC and subsets, it is generally accepted that elements should contain approximately 3–5 image features in order for them to be computed with a correct convergence. This value may vary depending on the type and size of elements being used but is generally a good starting point to determine if a mesh can be used directly conjointly with a series of images.

C.4.3 Additional Regularization

Using a refined simulation mesh for a measurement can be a problem when the reprojected elements' sizes are too small in the ROI of the image. To overcome this problem, mechanical regularization has been introduced in global DIC analyses [87, 90, 105]. This regularization technique is a "mechanical filter" within the DIC algorithm. It requires the measured displacement field to locally follow a mechanical regularity imposed on the displacement and strain fields in the absence of cracks (see Fig. C.6).

The weight associated with the regularization term leads to a length scale that defines the cut-off frequency of this mechanical filter. If this regularization length is less than the element size, the latter controls the uncertainty level and the interpolation error. Otherwise, the regularization length becomes the primary length to consider and plays a similar role as the element size.

Caution C.8 — Regularization Implementation

Regularization is highly dependent on the chosen implementation, and the user should refer to the DIC vendor manual to choose the correct regularization length for their problem and for more information on these matters.

Caution C.9 — Bias Errors due to Regularization

Regularization will force a solution to follow the solution required by the regularization. This may introduce bias errors if used inappropriately.

C.5 Analysis Results for Global DIC Methods

C.5.1 Gray Level Residual

The gray level residuals allow the user to check if the measured displacement field obtained after convergence of the algorithm is a valid solution to correct the deformed images by this displacement field with respect to the reference image (see Fig. C.6). Residuals can be reported by camera for stereo-DIC or directly on the mesh. In the first case, each residual field corresponds to the difference between the corrected deformed image and the reference for each camera. In the case the residual is given per element, it is generally computed as the difference between the speckle pattern defined on the 3D mesh as the mean value of the reference images and the mean values of the advected deformed images. Gray level residual fields examples are provided in Fig. C.7.

Tip C.6 — Validity of Kinematic Assumptions

The user can check the validity of the kinematic assumptions (e.g. displacement continuity or cracks) using the gray level residual.

Tip C.7 — Gray Level Residual and Image Noise

Ideally, after a measurement, the residual level should be close to the noise present in the image, notwithstanding other sources of error (i.e., camera position-dependent lighting issues, pattern degradation).

C.5.2 Uncertainty

In global DIC, the uncertainty at each node of the FE mesh can be estimated either:

1. Analytically through the inverse of the correlation matrix and using the noise level given by the camera detector [102]. In this case, the camera detector noise is supposed to be white and follows a Gaussian distribution, and the uncertainty on the displacement field is only due to this noise.

2. Experimentally or numerically through the measurement of a known displacement applied to the test piece [70]. Usually this displacement is based on rigid body, stretch, shear or even harmonic motions. This route was followed in the DIC Challenge, where numerically-generated images were also used to evaluate uncertainties [44], or in other measurement uncertainty guidelines [65].

Method 1 is derived from the global DIC equations, but its results remain theoretical. From a general point of view, measurement uncertainty should be reasonably similar between local and global DIC, and it is recommended to use Method 2. The main body of this guide presents usual techniques to quantify measurement uncertainties (see Sec. 5.4 of the main body of this guide). Differences between DIC techniques for global DIC include varying element size and shape function instead of subset size, subset shape function and step size.

C.5.3 Spatial Resolution

Some authors also address the question of spatial resolution and compare local and global DIC methods [27, 69, 76, 84]. These matters are recent and do not constitute a consensus on how to define spatial resolution in global DIC. The DIC Challenge 2.0 [45] tackles this issue and can be consulted for the most recent results and discussion.

C.5.4 Strain Computation

As for any DIC analysis, several definitions for strain calculations can be chosen. Strain computation in global DIC may use the same kind of techniques already available in local DIC methods (see Sec. 5.3.3 of the main body of this guide). For global FE-based DIC, the most direct way is to exactly derive the existing element shape functions in order to construct the local deformation gradient, from which various strain descriptors can be calculated. This allows for a one-to-one matching with usual FE simulations strain calculations. It is also usually possible to apply some kind of filter to compensate for the naturally noisy data. To extract a local strain value, some packages also allow interpolations of the displacement field in a selected region before deriving a strain.

Caution C.10 — Filtering of Displacements for Strain Calculations

Similar to the local DIC method, users should be aware of the implications of using any kind of filter or transformation of the raw measured data (i.e. the displacements). The use of filtering, mechanical regularization or virtual strain gauges should always be handled with care since these settings may have a strong influence on the extracted quantity value and noise-floor (as defined in the main body of this guide). Users should refer to the DIC vendor manual and training for more information on these matters.

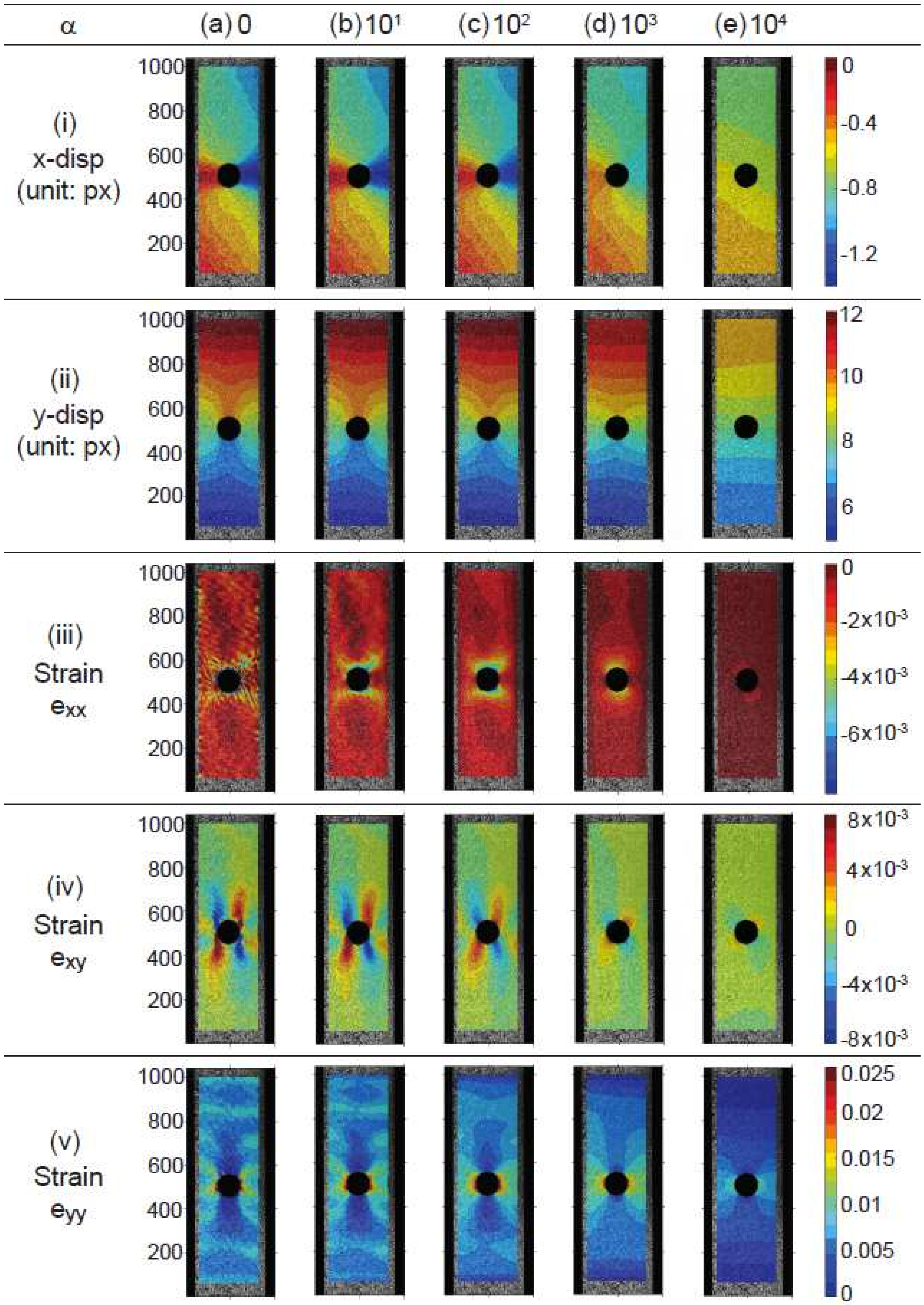

Figure C.6: Mechanical regularization method effect on an open hole tensile test in the X-direction: displacement and strain fields with (a) no mechanical (or additional) regularization and (b), (c), (d), and (e) with increasing regularization lengths. As a "mechanical" filter, regularization allows the removal of high-frequency components that are not mechanically admissible (see (a) versus (b)). Conversely, choosing a too large regularization length can also remove useful mid-frequency content (see (d) and (e)).

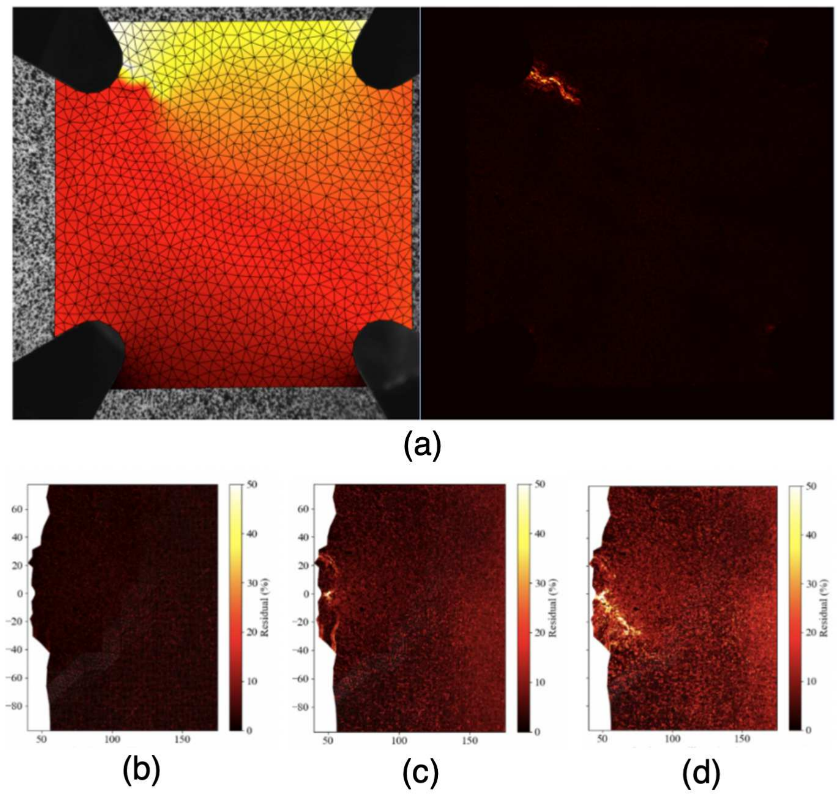

Figure C.7: Gray level residual field examples. (a) Magnitude of displacement field (left) and gray level residual field (right) of a composite cross test piece (courtesy of F. Hild, LMT-Cachan). Localized increases in residuals highlight the crack path, with a characteristic size depending on chosen element size and regularization options. (b)-(d) Residual field of a crack propagation experiment in a steel tube (courtesy of EDF). Increases in the residual moving from (b) to (d) characterized with larger spatial wavelengths indicate other errors, for instance due to lighting evolutions.

Notes