

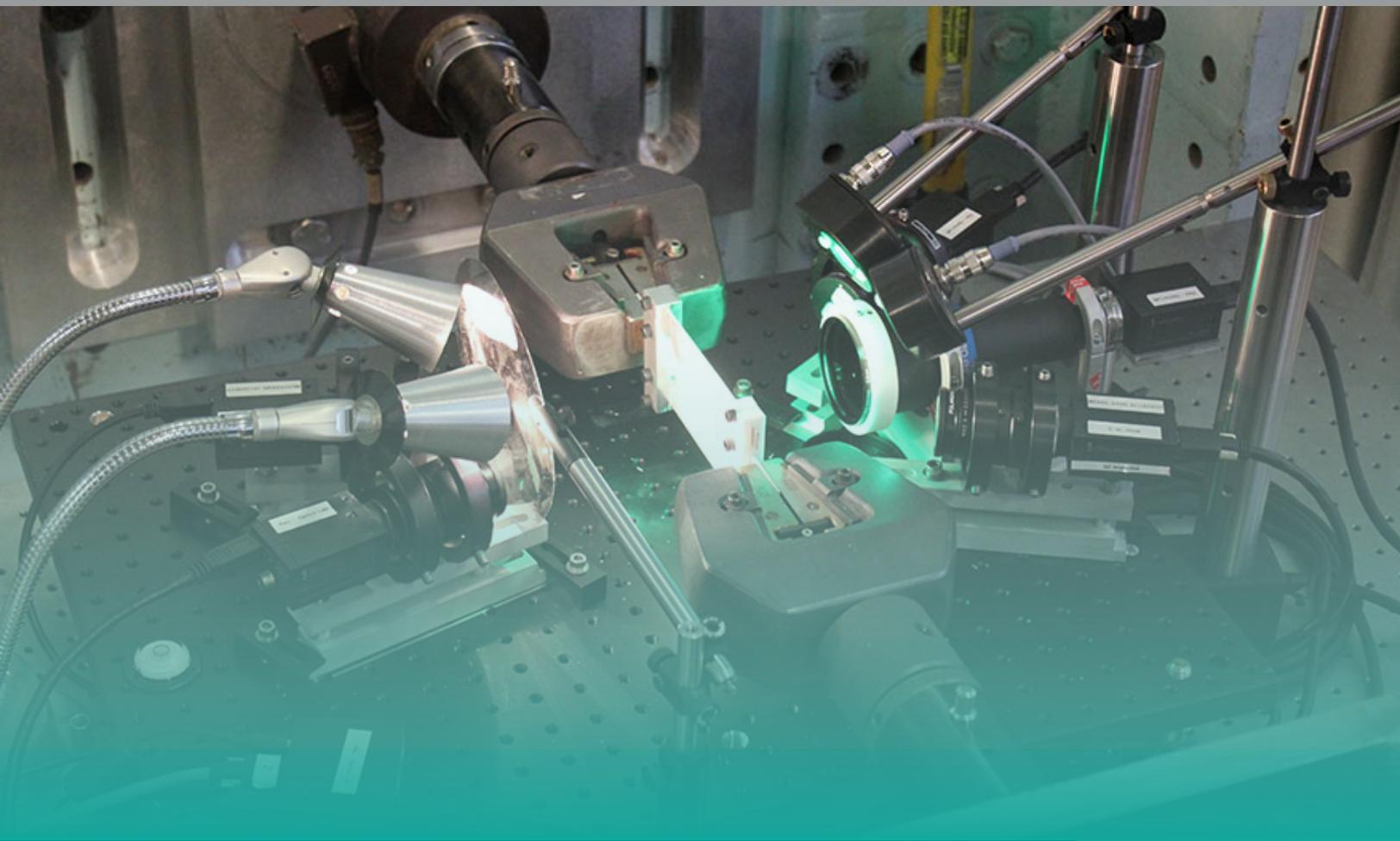
iDICS

INTERNATIONAL
DIGITAL IMAGE CORRELATION
SOCIETY

A Good Practices Guide for Digital Image Correlation

Standardization, Good Practices, and Uncertainty Quantification Committee

October, 2018



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, Good Practices, and Uncertainty Quantification 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.

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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.

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.

To begin, the basic concepts of DIC are introduced here. For a more complete introduction to DIC, one should consult [42]. For a practical guide to getting started with DIC, the reader is also directed to the series of articles in [16]. 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. 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 cameras¹ oriented at a stereo-angle to perform 3D photogrammetry in addition to image correlation; this is called stereo-DIC.² 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

¹Stereo-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.

²Stereo-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.

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 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).

In brief, a software code analyzes a user-defined region-of-interest (ROI) within the images, which contains a set of interrogation, or measurement, 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). This correlation is performed by first approximating the pattern in each subset using an interpolant function, and then allowing that function to deform from the reference image based on a subset shape function. A matching criterion 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.

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). Therefore, determination of the resolution of the QOIs through uncertainty quantification analysis 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-DIC³
- Single DIC system: One camera for 2D-DIC and two cameras⁴ for stereo-DIC⁵
- Standard machine vision cameras and optical lenses (no images from, for example, microscopes, stereo microscopes, or high-speed cameras)
- Local, subset-based DIC algorithms (as opposed to global algorithms)

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

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

⁴See footnote 1 on page 1.

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

⁶There 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).

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.

Recommendation 2.1

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. 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

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

Recommendation 2.2

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

2.1.5 2D-DIC vs Stereo-DIC

Determine if 2D-DIC or stereo-DIC will be used.

Caution 2.1

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 [13, 43, 44].

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}

^aIf 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.

^bLack 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.

^c2D-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

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 Sec. 5.4.3.

See Sec. 2.2.1 for recommendations on lens selection for 2D-DIC.

2.1.6 Stereo-Angle

For stereo-DIC, select the required stereo-angle.

Tip 2.2

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

Typically, the stereo-angle should be between approximately 15–35 degrees [23]. 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 [3].

Caution 2.2

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.

Tip 2.3

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 camera resolution and FOV, and DIC processing parameters such as subset size and step size.

Tip 2.4

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 higher image resolution 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 high image resolution, the system may be lens-limited, meaning that further increase in magnification or image resolution will not improve the spatial resolution.

^aAlternatively, 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.

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

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, etc.) and processing parameters (i.e. subset size, step size, etc.). See Sec. 5.4 for more information.

2.1.10 Frame Rate

Determine the desired frame rate.

Tip 2.6

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 Shannon's sampling theorem for noisy signals, i.e. the imaging frame rate must be about 10–15 times the frequency of oscillation.

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 position in the deformed images. However, most DIC software allows for an initial guess that is chosen by the user, 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 size. For example, if the subset 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.

2.1.11 Exposure Time

Determine the maximum allowable exposure to limit motion blur.

Tip 2.7

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. 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 [45].^a

The displacement, in pixels, per exposure is calculated as:

$$\text{Displacement per Exposure [px]} = \left(\text{Velocity} \left[\frac{\text{mm}}{\text{s}} \right] \right) \cdot \left(\text{Image Scale} \left[\frac{\text{px}}{\text{mm}} \right] \right) \cdot (\text{Exposure Time [s]}) \quad (2.1)$$

^aThe 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

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

⁷The 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.

2.2 Equipment and Hardware

2.2.1 Camera and Lens Selection

Select a camera and lens⁸ pair to obtain the desired FOV, DOF, SOD, spatial resolution, temporal resolution and noise-floor determined in Sec. 2.1.

Tip 2.9

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 sensor size, and SOD, see Appendix B. Additionally, more information on camera and lens selection is found in [21, 22].

Tip 2.10

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

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

^aThe 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

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.

⁸Some lenses have anti-vibration features, but the effects of these features on DIC measurements have not yet been thoroughly investigated.

Caution 2.4

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

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

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

If 2D-DIC must be used, a bilateral telecentric lens is recommended to mitigate small errors due to out-of-plane translation; 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.

Caution 2.5

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

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, 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

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

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 2.8

Set the FOV such that the image ROI is the same in both cameras, as close as possible given the different perspective each camera sees.

Set the orientation of cameras with rectangular detectors (chips) so that the long axis of the detectors are aligned with the long axis of the ROI of the test piece (Fig. 2.1). If the ROI is short and wide, mount the camera in landscape orientation; if the ROI is tall and narrow, mount the camera in portrait orientation.

Set the stereo-plane perpendicular to the plane of the test piece (Fig. 2.1).^a Camera orientations with compound angles (i.e. a stereo-angle between the cameras and a tilt of the stereo-plane with respect to the test piece) increase perspective distortions of the images, and thus are less desirable, and should be avoided.

Test piece ROIs with a large aspect ratio should be oriented with their long axis (opposed to their short axis) perpendicular to the stereo-plane (Fig. 2.1). This orientation reduces large perspective differences at the edges of the ROI in each camera.

^aThis guideline only applies to nominally planar test pieces imaged with a single pair of stereo cameras. More complicated test piece geometries, DIC systems with more than two cameras, and multi-system DIC measurements are outside the scope of the current edition of this guide.

- 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.

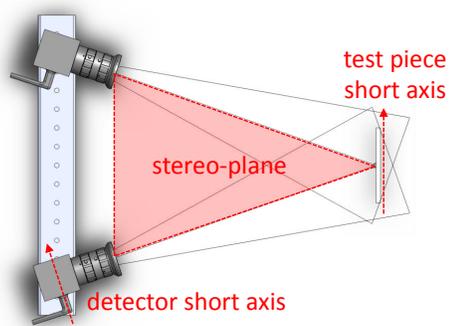
Caution 2.7

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!

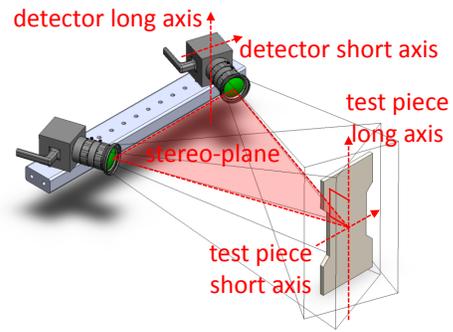
^aIf both cameras move together rigidly with respect to the test piece, only rigid-body DIC displacements are affected. For most applications where rigid-body motion is not important (e.g. strains are the QOI), this rigid-body displacement error is inconsequential.

^bRigid-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.

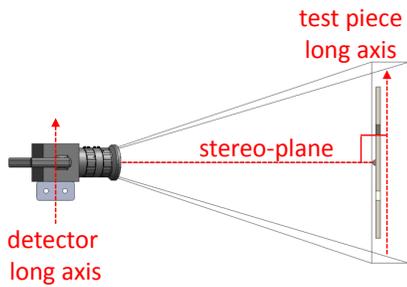
⁹Test setups in which the cameras cannot be practically rigidly-mounted together, e.g. large-scale tests with large camera separation that require individual tripods for each camera, are not discussed in this edition of the guide.



Top View



Isometric View



Side View

Figure 2.1: Schematics depicting the recommended orientations of the camera detectors in a stereo-camera pair with respect to the test piece. In this schematic, the long and short axes of the test piece ROI are assumed to align with the long and short axes of the test piece itself.

- 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 2.9

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 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

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

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

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 2.10

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.) [20]
- 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

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.

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

¹⁰Refer to footnote 9 on page 14.

- 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

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.

Tip 2.17

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

Caution 2.11

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 [41]. 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 to 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.¹¹

¹¹The 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

2.2.4.1 Type of Lights

Tip 2.18

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.

^aSpecific 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 [12] 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 reflections.

^aCross-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

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

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.

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.

Recommendation 2.12

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

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) [34], though contrast of at least 50% (130 counts) is typically preferred.^a

^aMore 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) [1].

Tip 2.20

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

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

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. 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 [24]. 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

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.

2.2.5 Hardware Heating

Caution 2.16

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

^aHeated 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

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

Even small temperature changes can cause heat waves 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 that, when animated in a movie, can look similar to flames in a fire [9].

Recommendation 2.15

Because errors caused by heat waves are not easily filtered in post-processing [9], 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

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

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

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

Recommendation 2.16

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 [4, 7].

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 [33]. This guideline applies to both the light (white) and the dark (black) features.

Tip 2.23

There are many definitions of feature size and many methods of determining feature size. 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.

¹²More advanced “optimized” pattern designs are outside the scope of the current edition of this guide, but information can be found in [2, 5, 11]. Additionally, some DIC manufacturers prefer a regular (not random) pattern, but these are also not covered here.

Caution 2.19

Pattern features that are smaller than 3 pixels risk being aliased and adding error to DIC results [32, 40]. 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 (see Sec. 5.2.5) and thus will degrade spatial resolution of displacements and strains, but will otherwise not negatively effect the results (i.e. will not add noise).

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 2.24

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 resolution. For a given FOV and lens, a camera with a lower image resolution (e.g. 1 MP camera) will require larger features and spacing than a camera with a higher resolution (e.g. 12 MP camera).

Recommendation 2.17

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

^aMore 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 2.25

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 in different regions of the image can be uniquely identified.

Caution 2.20

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 of the ROI of the image) [36]. 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.

2.3.2.4 Quality

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

Tip 2.26

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.

¹³Note 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.

Tip 2.27

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

Tip 2.28

Even at strains where decorrelation does not occur, pattern degradation can result in reduced correlation quality and increased uncertainty in the measurement [7].

2.3.2.5 Reflections

The pattern sheen should be matte and not glossy, to avoid glare and specular reflections.

Caution 2.21

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

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

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

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

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

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.

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 2.29

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

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 specimen for large displacements, and is not recommended for DIC.^a

^aThere 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

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 2.30

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 2.31

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 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.)

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

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 specimen, to prevent any people or objects moving behind the test specimen 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.

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

Recommendation 3.1

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

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. 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.

Tip 3.1

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 propellant 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

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 operate them 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

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. 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, 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

If the cameras are not warmed up, errors can be introduced into DIC results due to thermal expansion of the cameras and lenses, 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

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

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

^aThese 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

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.

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

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 test 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

To make sure that the test piece is in the middle of the DOF, and that the focus is constant across the ROI, start with the aperture wide open and adjust the focus to find the bounds of the DOF. With the aperture open, the DOF is limited; thus it is easier to see when the test piece goes out of focus. 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:

- Glare
- DIC pattern that is too coarse (i.e. fewer than 3 features per intended subset size) or too fine (i.e. features that are smaller than 3 pixels)
- 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
- Vibrations or other camera motion (some of which can be detected by zooming in on a live image and looking for non-random motion)

Recommendation 3.4

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

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

¹⁶If 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. However, this is an advanced topic that is outside the scope of the current edition of this guide.

¹⁷Typically, 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.

Caution 3.6

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. However, neglecting to correct lens distortions may add error to the measured displacements and result in additional error in the calculated strains.

Recommendation 3.5

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 FOV by the camera resolution. 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

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

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 [15]. 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.

^aTargets 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

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

There are two strategies for creating a clear working space:

1. Remove the test piece from the test 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 test 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

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 the calibration (see Sec. 3.3.2) is strongly recommended after returning the test specimen 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 specimen 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

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

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

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.

3.2.2.4 Acquire Calibration Images

Acquire calibration images such that there are well-extracted features in the entire working volume of the optical system, i.e. a volume outlined by the FOV and the DOF.¹⁸

Recommendation 3.10

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:

1. Rotate about the horizontal image axis.
2. Rotate about the vertical image axis.
3. Plunge towards and away from each camera, along its optical axis.
4. 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.
5. Rotate 90 degrees about the optical axis and repeat the above steps.^a
6. Perform combinations of the above positions and orientations (i.e. rotate about the horizontal and vertical axes simultaneously while plunging along the optical axis).

^aManufacturing 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

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

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

¹⁸The 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.

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

It is more important to have high-quality images (i.e. in focus, good contrast, no glare, filling the entire working volume of the optical system, etc.) than to have a large number of images. Take care to keep the calibration target within the working volume of the optical system, 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 working volume of the optical system.

Caution 3.12

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.

Recommendation

Take a sufficient number of images to have features that fill the working volume of the optical system, 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.

Tip 3.7

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 working volume of the optical system. (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

¹⁹Selection 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.

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

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 [29].²⁰

Recommendation 3.12

Typical parameters to check include:

- **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

²⁰Individual 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. 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.

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.
- **Angles:**^a The reported stereo-angle should be approximately the same as the physical angle between the two cameras. 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:**^a The reported straight line distance between the two cameras should be approximately the same as the distance between the two camera detectors.

^aThis parameter applies only to stereo-DIC and is not applicable to 2D-DIC.

Tip 3.9

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

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

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

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

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

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

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

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

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

The final DIC user-defined parameters, i.e. subset size, step size, virtual strain gauge size, etc. (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.

Recommendation 3.16

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

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

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

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

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 calibration parameters.

3.3.2.3 Absolute distances

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

Recommendation 3.17

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

²¹See footnote *b* on page 14 for a note concerning correction of extrinsic parameters of a camera calibration.

²²If images of the calibration target were of a different image resolution 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.

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

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

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 such as subset size, step size, virtual strain gauge size, etc. (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). 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 test frame are set to record and are synchronized with DIC images.
- Triggering of the test frame and/or DIC images is ready.

Caution 4.1

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 [14], a set of images to verify DIC software has been carefully designed and vetted. These images are available at <https://sem.org/dic-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 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 experts²³ — 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.

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

Caution 5.1

It is critical that the reference was acquired prior to any applied displacement or force. Otherwise, all DIC measurements correlated with respect to the reference image will be biased by an unknown amount.

Tip 5.1

One can acquire several (approximately 10) 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.

- 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.
- Partitioned correlation:** As a compromise between using a single reference image of the undeformed specimen 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 soften the edges of a particularly sharp DIC pattern, can be beneficial.

Tip 5.2

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.

Caution 5.2

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

^aMore specific guidelines regarding digital pre-filtering of images may be included in a future edition of this guide.

Recommendation 5.1

If a physical anti-aliasing filter was used during image acquisition, digital pre-filtering is not recommended.

5.2.3 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 [10, 17, 42] for more information.

5.2.4 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 [18] and [42, Sec. 5.6.1 (Interpolation Bias)].

5.2.5 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. 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 pixels² 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

A larger subset size of 21×21 pixels² is recommended as a more practical minimum size for typical DIC measurements [17]. This is true particularly if the DIC pattern size and density is variable and not constant over the entire ROI.

Tip 5.3

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, though this is an advanced topic.

5.2.6 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. 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. (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 the gradients of the QOIs.) 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 recommended, to generate quasi-continuous field data without interpolation.) Additionally, the step size also influences the Virtual Strain Gauge size (Sec. 5.4.5).

5.2.7 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.

5.3 Strain Calculations

There are many different approaches to calculating strain from displacements, depending on the specific DIC software that is used. 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.

5.3.1 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, strain window, strain shape function, pre-filtering of the displacements, post-filtering of the strains, and filter window. 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.

5.3.2 Examples of 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.

5.3.2.1 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).

5.3.2.2 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. 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.

5.3.2.3 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. 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).

5.3.2.4 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, and order of the spline.

5.4 Uncertainty Quantification

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 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 sharp spatial gradients of a QOI, 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 static images of a DIC pattern that were acquired under the same conditions as the test images. With no applied force or displacement on the test piece, all measured QOIs requiring deformation 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 5.3

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.

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, 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.

Using the final DIC user-defined parameters, analyze all of the static images that were acquired after the calibration process (Sec. 3.3.1). Compute any QOIs in the same manner as was used in the analysis for the mechanical test images. 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 static images. To quantify the temporal variation, compute the standard deviation of the QOI for each subset over time. Then average this temporal standard deviation for each subset over all the subsets in the ROI of the image.

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.

Typically, the standard deviation is similar between the horizontal and the vertical directions. 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.

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.

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). 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. 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 specimen.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 sizes, low-order subset 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 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. 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 is 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 [14].

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. 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 highest spatial strain gradients that occur in the test piece are captured, and aids in the determination of what the optimum balance is between capturing spatial strain gradients (i.e. minimizing bias due to over-smoothing) and improving the strain resolution (i.e. minimizing the variance errors). The procedure outlined here is based on [38]. Some DIC packages automate this process, while with others, the user must perform it manually.

²⁴For 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.

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. Select the image in which the highest strain gradient is initially calculated.
2. Select the reference image, an image at nominally zero force (acquired after the reference image), and the image of highest strain gradient determined in the previous step.
3. Analyze these images with different DIC settings, varying the VSG size.

Tip 5.4

The three dominant variables that affect the VSG size are the subset size, step size, and strain window and/or filter window. Depending on the strain calculation method, other variables may also affect the VSG, including but not limited to the subset shape function and strain shape function.

4. 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.

Caution 5.3

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

5. As the VSG size decreases, the maximum strain amplitude along the line cut will typically increase.
 - If the maximum strain amplitude converges with further decreases of the VSG, then the actual maximum strain amplitude has been captured. Any VSG that is larger than the largest VSG that results in the converged actual maximum strain amplitude will underestimate the actual strain amplitude, and introduce bias into the measured strain results.
 - If the maximum strain amplitude never converges, even with the smallest VSG allowed by the software, then the actual maximum strain amplitude is unknown. At best, one can report that the actual strain amplitude is greater than or equal to the maximum measured strain amplitude. That is, the reported strain is a lower bound on the actual strain amplitude.

Tip 5.5

If the smallest VSG allowed by the software is not sufficient, the test could be repeated with a smaller FOV / higher magnification. For a given step size, strain window or filter window size, etc. — all defined in terms of pixels in the DIC software — higher magnification images would produce a smaller physical VSG size.

6. As the VSG size decreases, the strain noise typically increases, because the amount of spatial filtering decreases. The noise can be qualitatively assessed from the line scans used in the previous step. To quantify the noise, compute the standard deviation of the strain field of the zero-force image for each of the DIC analyses performed.
7. The final decision on which VSG size (and other DIC parameters, if those were varied as well) to use is a matter of expert judgment. If capturing the highest strain gradient 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 uncertainty 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).

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 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.

Tip 6.1

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!

6.1 DIC Hardware Parameters

6.1.1 Required

- Camera Manufacturer and Model, and Image Resolution
- 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
- 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 [14] (<https://sem.org/dic-challenge/>). Any subsequent documentation of DIC measurements that use the code should refer to this verification.

- Image Filtering, if applied
- 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)
- Data Processing and Filtering for QOIs

Recommendation 6.1

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.

- 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.

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)
- Interpolant
- Matching Criterion

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.

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.

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.

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.

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 [42, 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.

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.

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.

Interpolant: Interpolation function used to calculate the subpixel changes within the subset shape function transformation subject to the matching criteria during the correlation calculation.

Matching Criterion: Mathematical formulation used to calculate the quality metric of the calculated displacement field based on the underlying image data. Also commonly referred to as “correlation criterion.”

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).

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. $1/(\text{pattern feature size})$).

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 [8], 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.

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.

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.

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

Note 1: Image resolution should not be confused with [optical resolution](#) or [spatial resolution](#).

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 desirable, whereas a larger resolution value is generally less desirable. These trends are opposite those of [image resolution](#) 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.

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, 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.

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.

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.

Stand-Off Distance [m]: The distance between the aperture of the lens and the test specimen.

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).

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

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.

Note 1: The step size is also sometimes reported as overlap. For example, 50% overlap means a step size of half the [subset size](#).

Subset: Portion of the image that is used to calculate one 3D coordinate value, or one displacement value.

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.

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.

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.

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.

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](#)).

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. 7.1, where L_{window} is the window size in terms of data points, and L_{step} is the [step size](#).

$$L_{window}^* = (L_{window} - 1) L_{step} \quad (7.1)$$

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](#).

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](#).

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

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

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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 test 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 test 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.

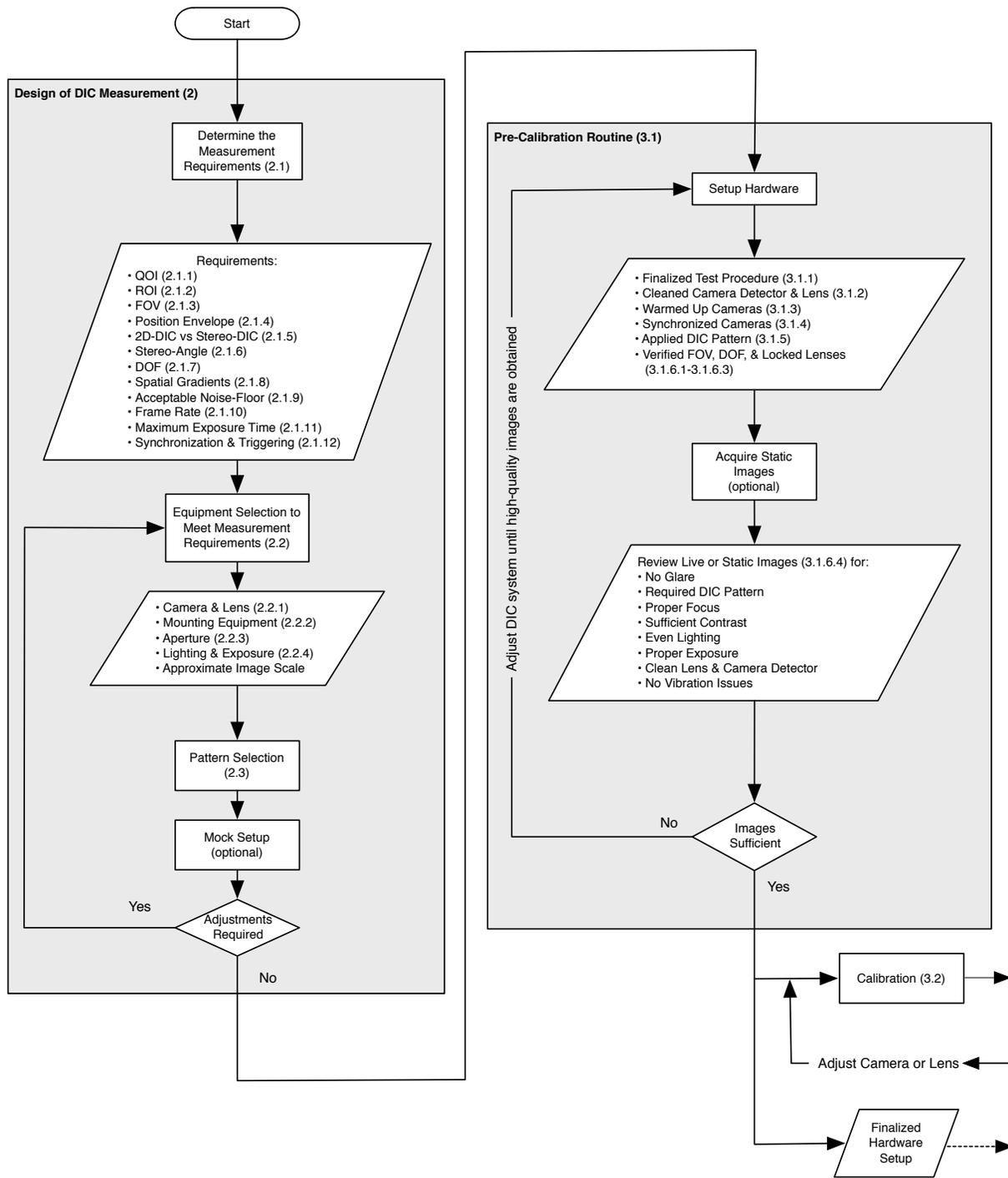


Figure A.1: Flow chart illustrating the main steps involved when conducting DIC measurements in conjunction with mechanical testing of a planar test piece (part 1).

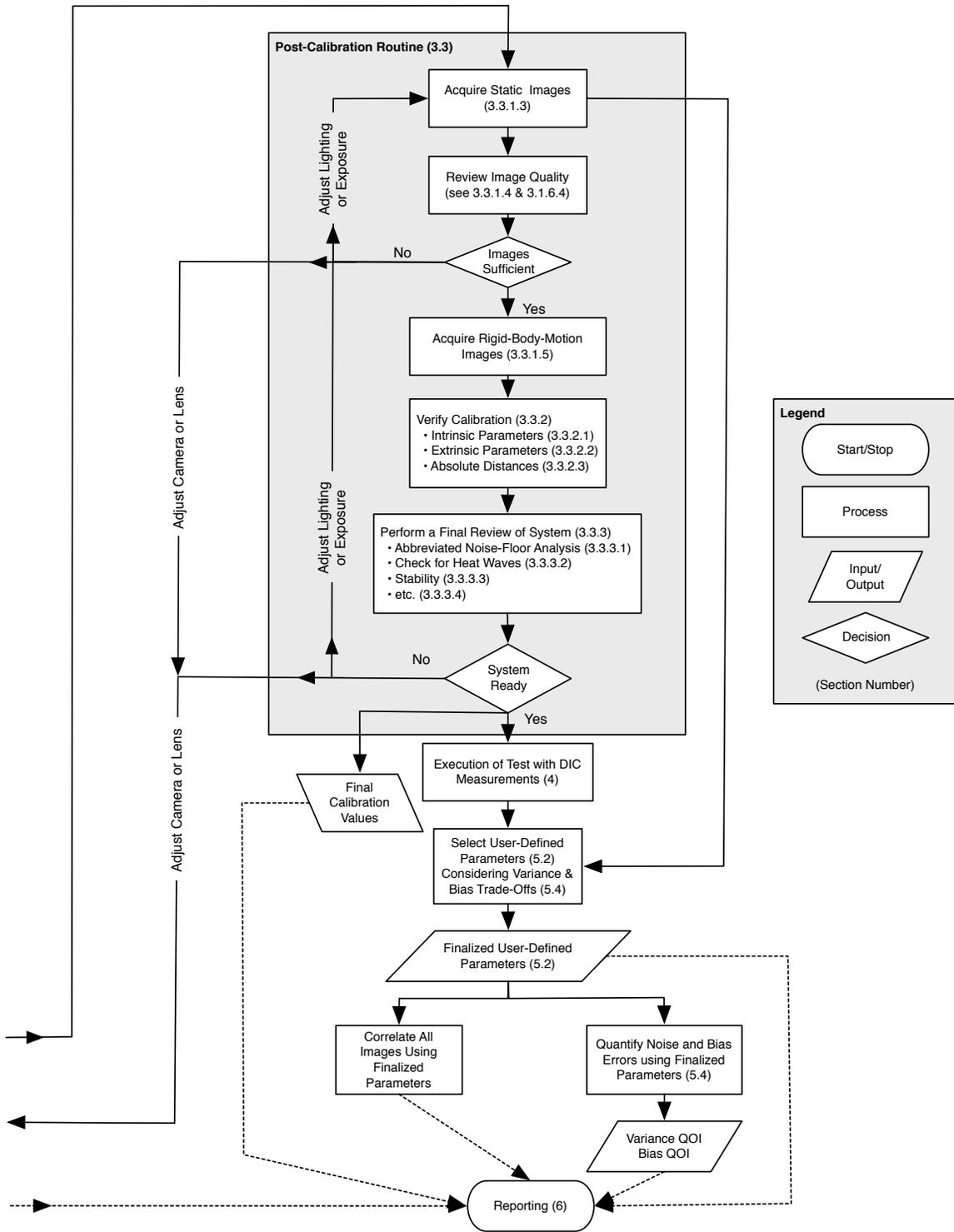


Figure A.2: Flow chart illustrating the main steps involved when conducting DIC measurements in conjunction with mechanical testing of a planar test piece (part 2).

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 sensor 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 or sensor 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 sensor(s) (L_{CS}):

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

Online calculators²⁸ are available to quickly solve for the FOV, and extend the formula to account for rectangular sensors. 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 or sensor bar. In this case, rearranging equation B.1 gives:

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

²⁵ *Thin Lenses* by Prof. Richard Fitzpatrick: <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](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)

The camera sensor 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 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 sensor 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 sensor, 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 sensor width of $L_{CS} = 4.80$ mm, reduced from the full sensor 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 sensor, 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.

Notes

