SAND2015-7954J

THE ART AND APPLICATION OF DIC

Virtual Strain Gage Size Study

by Phillip Reu

Introduction

DIC is a non-linear low-pass spatial filtering operation; whether we consider the effect of the subset and shape function[1], the strain window used in the strain calculation[2], or other post-processing of the results[3], each decision will impact the spatial resolution[4] of the measurement. More fundamentally, the speckle size limits[5] the spatial resolution by dictating the smallest possible subset. After this decision the processing settings are controlled by the allowable noise level balanced by possible bias errors created by the data filtering. Stated in another way, the value reported by the software will always be some filtered and modified version of the true displacement or strain field. The question remaining at the analysis step is how much spatial resolution will be exchanged for a reduction in noise, i.e. filtering? This article describes a process to determine optimum DIC software settings to determine if the peak displacements or strains are being found.

Virtual Strain Gage (VSG) Study

The point of a VSG size study is to determine the optimum balance between filtering and noise in the DIC results. At this point the images are already acquired, and we can only control how we will post-process the images. Indeed, after this process is completed, it may be decided to return to the experiment and change the speckle size and FOV to obtain better spatial resolution!

The VSG-study process is simple. Bring into the DIC analysis software the reference image, an unloaded "noise" image, and a maximum deformation image. By maximum strain, I mean an image that is at the "final" deformation state where we would like to determine whether the strain gradients[6] are being captured. We limit the analysis to these three images to more quickly analyze the results over a number of software settings. Next, run a preliminary analysis and find regions of interest that have high strain gradients and extract the results of interest along this line. Once the smallest subset size has been determined, setup a grid of DIC software settings to vary that will influence the results. The list on the right is a good starting point of settings that can be varied; most codes have similar settings that may go by slightly different names. Run the analysis at each software setting and extract the strain (or displacement) values along the line for both the noise image and the maximum deformation image. Calculate the standard deviation of the data along the line of the unloaded image to determine the measurement resolution. Plot the data for the maximum load runs together to check for "convergence." This process is

Spatial resolution study

1. Select 3 images: Reference, zero load, and maximum deformation.
2. Select an appropriate subset size.
3. Determine a region of interest with high gradients to extract data.
4. Vary DIC code settings[1,2,3].
5. Compare the results and determine convergence.

[1]Reu, P. Experimental Techniques **36**(2): 3-5.

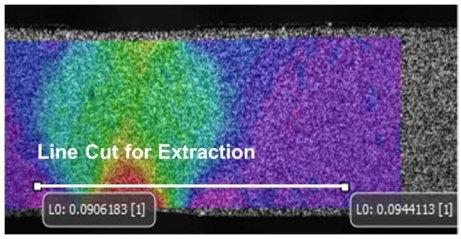
[2]Reu, P. Experimental Techniques **36**(4): 3-5.

[3]Often a Gaussian spatial filter or something similar. Check your software manual.

[4]Spatial resolution is defined as the shortest period over which the displacement or strain gradients can be captured without unacceptable bias errors.

[5]Reu, P. Experimental Techniques **XX**(Y): 3-5.

[6]The same process is applied for ε_{xx}, ε_{yy}, ε_1, displacement, etc.



Maximum load image showing the line-cut used for the virtual strain gage size study.

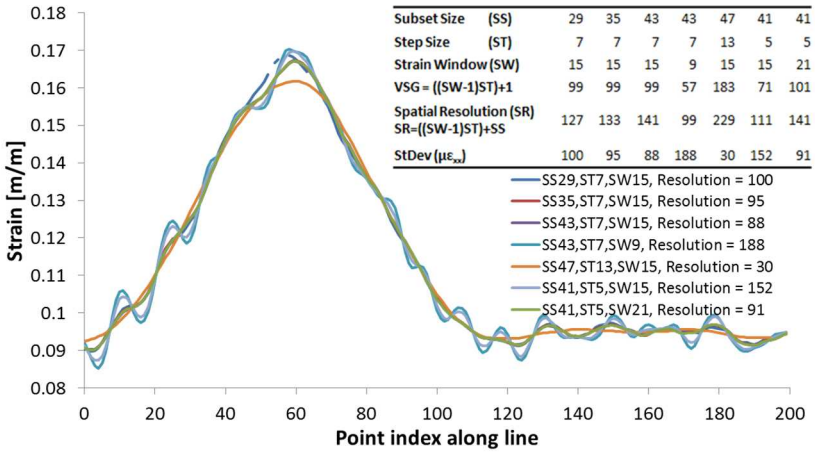
Software settings to vary

1. Susbset (facet) Size
2. Step Size
3. Strain Window Size
4. Post-DIC filtering

Primary

5. Minimization function
6. Interpolant
7. Any other settings

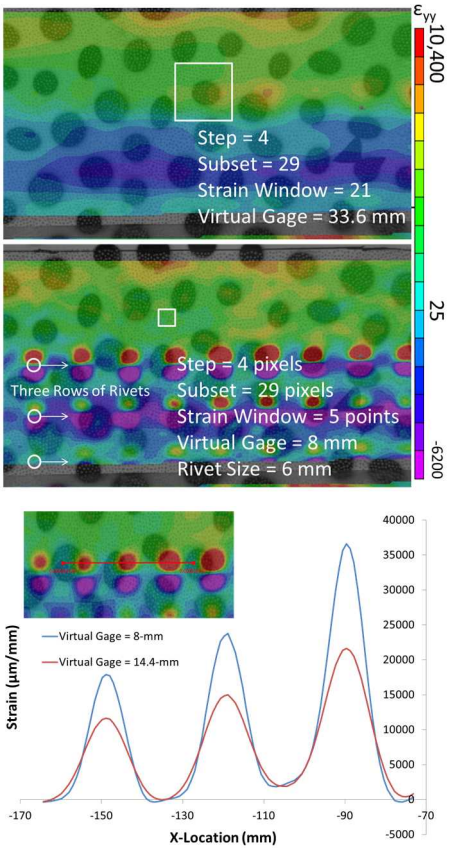
The Art and Application of Digital Image Correlation is written by Phillip L. Reu (Phillip.Reu.DIC@gmail.com). He received his PhD from the University of Wisconsin–Madison and is currently a Principal Member of Technical Staff at Sandia National Laboratory. He began working with digital image correlation in 2004 and is focused on understanding the influence of the unavoidable compromises made in field measurements on the final DIC uncertainty. *Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract No. DE-AC04-94AL85000.*



illustrated in the left figure, where the inset table gives the software settings that were varied, the virtual strain gage (VSG) size and the spatial resolution (SR). We can see that the large VSG (orange) underestimates the maximum strain by 6%; with increasingly smaller gages converging on a solution but with different levels of noise, with the smallest gage resolution being 188 με and the largest gage resolution 30 με. For this experiment an optimum setting that converges is a subset of 41, step of 5 and a strain window of 21.

This VSG study converges, in that we are able to reproduce the strain contour with increasing larger gages. This will not always be the case. A different experiment[7] illustrates a case where convergence was not obtained even with the smallest VSG allowed by the underlying speckle pattern. In this situation the strain is only correctly captured up to the point where the results of the two strain gage sizes diverge, and the true strain is greater than (or maybe equal) to the value from the smallest gage. Lack of convergence is a fairly common occurrence in DIC, particularly when used to measure near cracks, material failure points, and other strain concentrations that all exhibit extremely large strain gradients.

[7]SEM paper 2013



Results for two different VSG sizes showing an extreme lack of convergence.

[7]This would be a very interesting topic for some student!

Exercise for the Reader
Do a virtual strain gage size study on a DIC test. Did it converge?

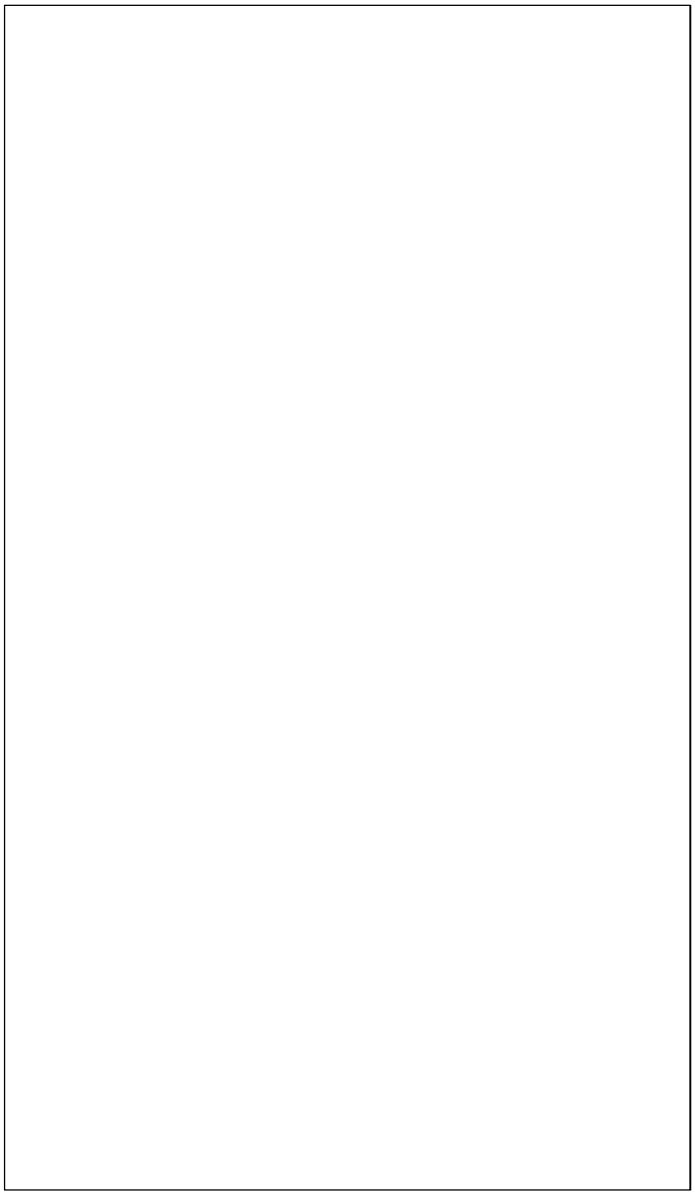
Convergence
Convergence is used colloquially rather than in a mathematically rigorous way in this discussion[7]. Careful consideration should be used in determining when the VSG study has converged. I have used a rather intuitive definition of when the VSG-size increase *does not* change the value of the measurement. You cannot assume that you have converged at only your smallest VSG size if not matched by increasingly larger sizes.

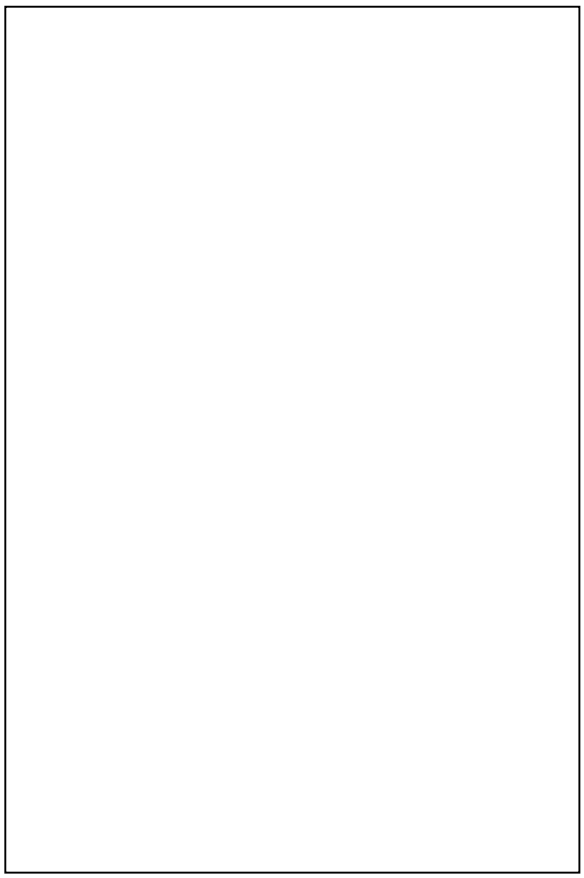
The Strain Gage Analogy
While it might seem from this discussion that DIC is inferior to strain gages in that DIC will spatially filter the results, this is incorrect, they both filter! The terminology "virtual strain gage" was chosen[2] because it behaves exactly the same as a physical strain gage; they both *average* the strain underneath the gage area. The strain gage community often forgets this and the values reported by the gages are assumed to be the *true* value: This may be incorrect. One of the great strengths of DIC is that you have a tool to determine whether you have converged on the correct strain value and have a small enough strain gage.

Conclusions
There is always a compromise between spatial filtering and resolution. Whether this is caused by increasing the subset size to limit the displacement noise, or having a larger VSG to obtain an acceptable strain resolution, the experimentalist must exercise judgment in choosing the best compromise. This article offers a simple and intuitive approach to assist in determining whether the bias errors from the filtering process are acceptable. A VSG-size study should be done for all tests and reported with the results.

Next Time: Series Conclusion.

Overflow Box





THE ART AND APPLICATION OF DIC

DIC: A Revolution in Experimental Mechanics

by Phillip Reu

Introduction

There is no doubt that digital image correlation (DIC) has and will continue to revolutionize measurements. Its ability to simply and intuitively capture the deformation and strain of a sample, with inexpensive camera hardware will ensure its continued growth. The support of a large number of commercial vendors who sell turnkey systems is a further testament to the popularity and power of the technique. The figure on the right shows the publication rate of journal articles that use DIC. An exponential growth rate is occurring as the technique spreads throughout the experimental community. I interpret this graph as having two sections; the early years of approximately 1988 to 2005, where DIC consisted of a small cadre of researchers inventing a new measurement technique. During this time people were writing their own code and had a deep expertise in conducting DIC experiments. After 2005, there had become a large installed base of commercial systems and independent codes distributed in universities, laboratories and businesses throughout the globe. At this point, many researchers were *users* rather than developers of DIC. This is a healthy and natural progression for any experimental technique, but it can present some problems. As with any complex technique training is required to use it successfully. Indeed, that was the motivation for this series of articles: To provide practical advice on how to conduct experiments without having to have written your own DIC software.

Training

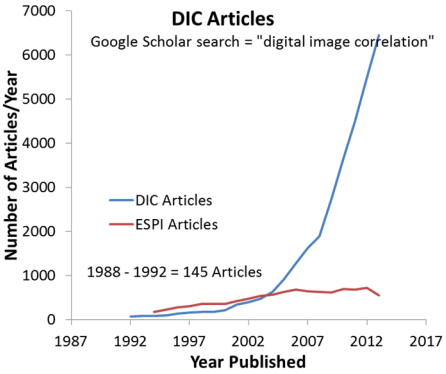
I think there is a strong analogy between how FE[1] use developed in engineering and how DIC will need to progress. Both are powerful techniques that will usually provide an answer: The question is always, how good is that answer. Unfortunately, this is to a large extent dependent on the training and the appropriate use by the experimentalist. I encourage beginning graduate students, engineers and research scientists to find a day[2] or week long training course[3] where you can learn the details of how to apply DIC. For training, the best approach is to do some practice experiments before as this will make your time at the course more valuable. Then, after the course, devote an extended time to doing DIC to reinforce the course learning. DIC is a skill that requires practice.

Standardization

As DIC permeates universities, industry, and government labs; data integrity becomes vital. If we want to use DIC as more than qualitative, it will require standardization in both the application and the analysis. There are a number existing and emerging efforts to make this happen. Your

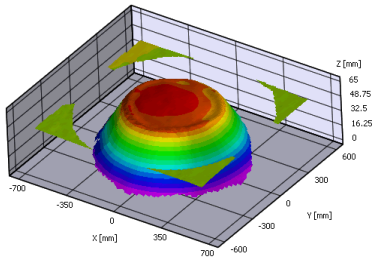
A Call to Action

1. Training – skilled users are needed.
2. Standardization – unified approach to analyzing and understanding the results.
3. Publication requirements.



Publication rate for DIC articles.

[1]DIC has finally provided the experimentalist with beautiful movies that can compete with any animation from FE. See below for single frame as an example.



Explosively driven 1.2-m diameter plate showing out-of-plane deformation.

[2]Many conferences will offer a one day pre-conference course (www.sem.org).

[3]"Metrology Beyond Colors" being an example of a week long DIC training course. (www.website.com)

The Art and Application of Digital Image Correlation is written by Phillip L. Reu (Phillip.Reu.DIC@gmail.com). He received his PhD from the University of Wisconsin–Madison and is currently a Principal Member of Technical Staff at Sandia National Laboratory. He began working with digital image correlation in 2004 and is focused on understanding the influence of the unavoidable compromises made in field measurements on the final DIC uncertainty. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract No. DE-AC04-94AL85000.

Standardization Efforts

1. DIC Challenge (www.sem.org)
2. International DIC Society (www.idics.org)
3. ASTM Group XX (www.astm.org)

Example 2D-DIC Report

Camera Type	Phantom Point Grey
Image Size	2400×2000 (pixels)
Lens	Nikon 28-85 zoom
Image Noise	0.7% (8-bits)
Image Filtering	Gaussian Kernel (9)
DIC Software	Favorite Vendor v 7
Scaling	0.085 mm/pixel
Avg. Speckle Size	4.25 pixels
Subset Size	21
Step Size	10
Strain Window	9
Virtual Strain Gage	81
Spatial Resolution	101
Correlation Algorithm	ZNSSD
Interpolation	Bi-cubic spline
Resolution	5-image noise floor
Displacement	0.011 pixels (0.93 µm)
Strain	225 µε (Lagrange)

Stereo Calibration Table

Intrinsics	
Cam_0 Image Center	623.8, 366 (pixels)
Cam_0 Focal Length	7299, 7297 (pixels)
Cam_0 Skew	-1.98 (deg.)
Cam_0 k1	0.05 (pixels^{-2})
Cam_1 Image Center	623.8, 423.7 (pixels)
Cam_1 Focal Length	7290, 7288 (pixels)
Cam_1 Skew	-1.45 (deg.)
Cam_1 k1	0.04 (pixels^{-2})
Extrinsics	
Stereo Angles	27.6, 2.2, -2.7 (deg.)
Translation	-44, 1255, 327 (mm)

Exercise for the Reader

Ask questions, learn and practice DIC.
Phillip.Reu.DIC@gmail.com.

participation in both the groups doing this and encouraging this in your companies and professional societies is critical to completing this important task. A list of ongoing efforts is shown on the left.

Journal publications

Journal publications distribute important engineering and scientific information. They should require enough information that a skilled reader can both understand and if desired reproduce the same results. For DIC, this means reporting enough details on the experiment and analysis that the quality of the results can be estimated; even if a complete uncertainty quantification has not been completed. The two tables on the left are a good example of the information that should be reported with the DIC results. As journal reviewers, if you do not see this information, the paper should not be accepted until it is supplied.

Cautionary Words

Great experiments require attention to detail. They also often require a number of iterations until you are able to measure exactly what you want. Don't be discouraged, learn from each setup and improve the next experiment. An incremental approach is strongly encouraged rather than one big test. When possible, have a secondary measurement that you can compare to: Extensometers, strain gages, accelerometers, etc. While an exact agreement is always difficult, this secondary measurement will aid in understanding the quality of your DIC measurement.

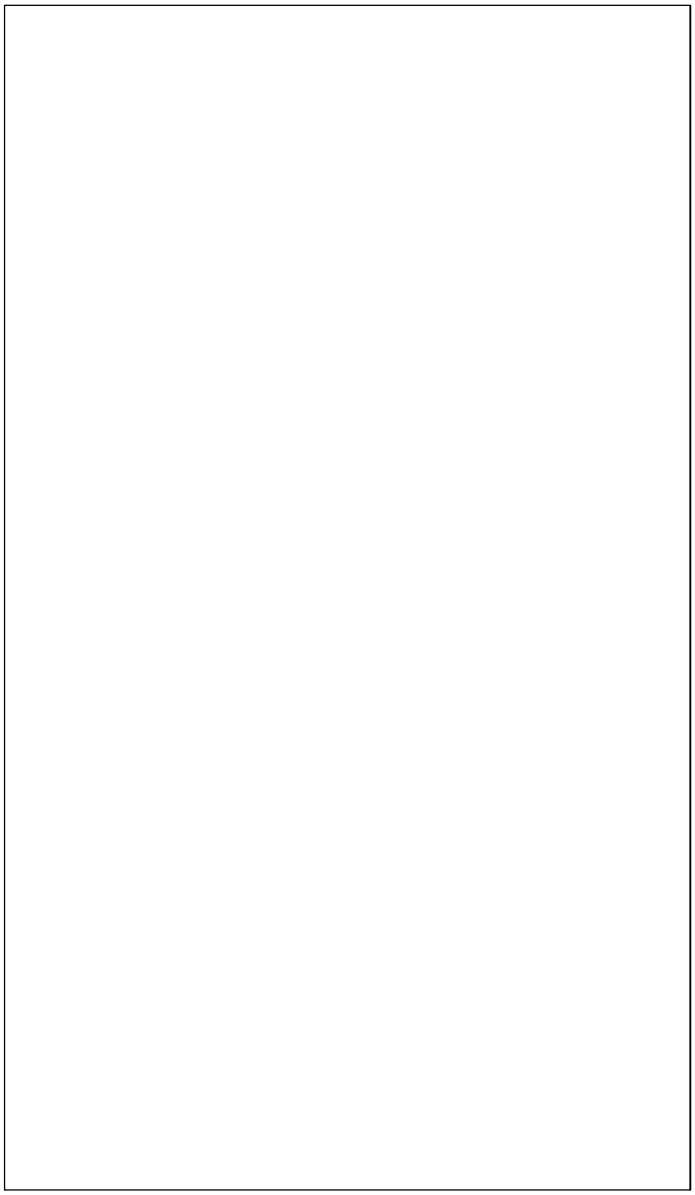
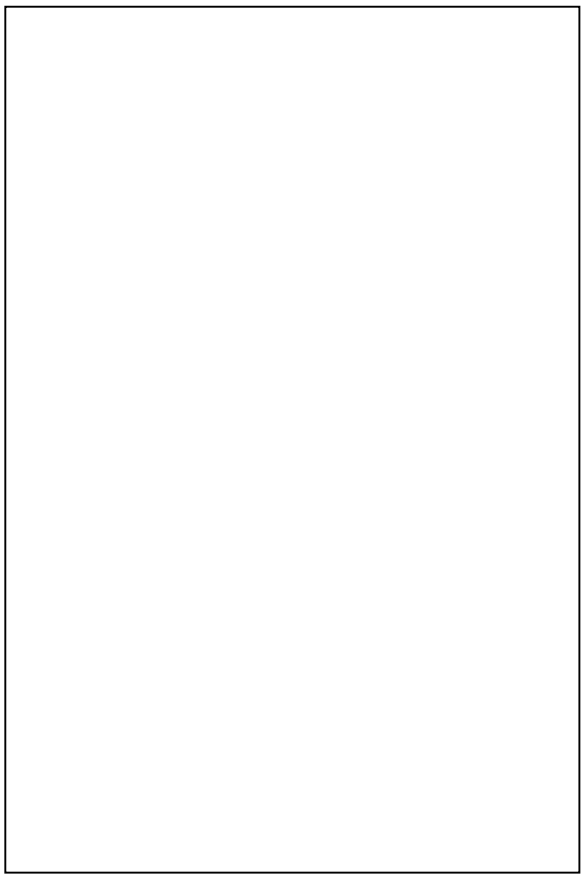
Spend some time doing simple DIC experiments: A 2D measurement of a stationary plate for example. These will teach you much about your DIC system.

As a final note: The noise is easy to measure, but may not be as important as the bias errors that are difficult to measure and may "invisibly" dominate the errors. The noise floor may be lying to you.

Conclusions

It has been a privilege to share this information with you over the last 24 articles. I hope you have found them valuable and I wish you the best of luck in your DIC measurements.

Best Regards,

Phillip Reu (replace with signature)

Overflow Box