Volumetric Deformation Measurements with Vic-Volume

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Overview

• Introduction
• Image Acquisition
• Volumetric Digital Image Correlation Basics
• Application Examples
• Conclusion
Volumetric Image Correlation

- 2D and 3D DIC only measure surface data
- Volumetric DIC can measure strain throughout the interior of a component
• Images can be obtained with CT scanner
Image Acquisition

- Micro and Nano-CT scanners
  - spatial resolution to 100 nanometers

- Synchrotron
Image Reconstruction

- The scans from different angles have to be transformed to obtain density distribution image (Radon transformation)
- Different algorithms for different beam geometries (parallel, fan-beam, cone-beam)
- Can be time consuming
- Artifacts
Ring Artifacts
• Fixed pattern biases displacements towards zero motion
Artifacts

- Star pattern around particles
- Change between scans
Artifacts

• Different reconstruction algorithms produce different levels of artifacts

• Currently, it appears that reconstruction is optimized for speed
Speckle Pattern
Seeded Rubber

- Sand particles
- Excellent contrast
- Minimal artifacts around particles
- Change in material properties
Contaminations in Aluminum

- Naturally present
- Very sparse, low contrast
- Significant artifacts
Aluminum Foam

- Great contrast
- Sparse in some areas
- Loss of correlation at high strains due to cells collapsing
• Good contrast
• Large voids
Volume Correlation Basics
• Cost function for optimization

\[ u = \arg \min \sum_{z} \sum_{y} \sum_{x} (F(x, y, z) - G(x, y, z, p))^2 \]

\[ p = \{ u, v, w, \frac{\partial u}{\partial x}, \frac{\partial u}{\partial y}, \frac{\partial u}{\partial z}, \ldots, \frac{\partial w}{\partial x}, \frac{\partial w}{\partial y}, \frac{\partial w}{\partial z} \} \]

• Parameter vector has 12 components

• Sub volume has extra dimension (z direction)
Volumetric DIC Algorithm

• Computational cost increases dramatically

• Example:
  • 31 pixel subset
  • 1000x1000x1000 voxel image
  • Step size 10

• Relative computational cost VDIC vs 2D:
  \[
  \frac{12}{6} \times \frac{31 \times 31 \times 31}{31 \times 31} \times \frac{100 \times 100 \times 100}{100 \times 100} = 6,200
  \]

• 1 second turns into 2 hours!!!
Implementation Challenges

- Keep CPUs loaded!!!
- Images do not fit in CPU cache
- Simple implementation keeps CPU waiting for data
- Caching and data copying strategies can change computation time by two orders of magnitude
- Efficient multi-threading
I heard this is really fast on a GPU, why don't you use that?
Typical analysis performance on modern 12-core computer

- 23x23x23 subset: 800-1,200 points per second
- 31x31x31 subset: 300-500 points per second

Image can be reduced by half in each dimension for 64x speedup
• Third dimension dramatically lowers noise (Type A error)

• Confidence interval below 0.001 voxel fairly common

• Much less smoothing required for suppressing noise in strain
How to select AOI in 3D volume?

Similar to “Motion-Tween” in animation software

Draw AOI on a slice

Move control points on another slice (keyframe)

Software interpolates AOI in between
Validation

- Difficult to validate a new measurement method without established standard to compare against
- FEA???
- Numerical simulation
How do you apply load inside a CT scanner?
• Scanning time can be long
• Sample must not deform during scan
• Sample must rotate for CT scan
• X-ray blocked by test frame columns
Simple Load Frame

- Loading mechanism fabricated from acrylic
- Designed to minimize deformation during image acquisition
Load Frame

- Off-the-shelf load frame with custom rotation integrated into CT scanner
Application Examples
Example: Rubber Puck

- Rubber puck loaded in compression
Rubber Puck

- CT image shows sand particle distribution
- 75mm diameter
- 20mm thickness
- Yxlon CT scanner
- Sand particles with size distribution between 0.65mm and 1.3mm were added to uncured rubber
Open Hole Specimen

• Acrylic load fixture used to apply displacement

• Dial indicator for displacement reading
Results: Horizontal Strain

VDIC

FEA
Results: Vertical Strain

VDIC

FEA
Discussion

• VDIC on simple puck specimen shows excellent agreement with FEA model

• Open hole specimen shows excellent agreement between Vic-3D measurement and VDIC measurement

• FEA model closely matches VDIC measurements for displacements and strains throughout entire depth of the open hole sample
Aluminum Foam Compression Test

- Aluminum foam sample loaded in compression
- Natural pattern used
- Localized deformation

Data courtesy of BAM Berlin
Rubber Matrix Composite

- Rubber matrix with nylon reinforcements
- Loaded in tension
- Speckle pattern from small beads
VDIC Results: Exx
VDIC Results: Exy
VDIC Results: Exz
VDIC Results: Eyz
Finite Element Comparison

VDIC

FEA
Summary and Conclusions

• Volumetric DIC is becoming more and more practical
  • Faster reconstruction
  • Faster analysis
  • Very high resolution micro focus capabilities
• Research needed to study and suppress reconstruction artifacts
Summary and Conclusions

• Application of speckle pattern is challenging
• Surprisingly low noise measurements possible
• Calibration of cone and fan beam
• Repeatability
• Accuracy