Application of High Speed Digital Image Correlation in Rocket Engine Hot Fire Testing

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Abstract

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Hot fire testing of rocket engine components and rocket engine systems is a critical aspect of the development process to understand performance, reliability and system interactions. Ground testing provides the opportunity for highly instrumented development testing to validate analytical model predictions and determine necessary design changes and process improvements. To properly obtain discrete measurements for model validation, instrumentation must survive in the highly dynamic and extreme temperature application of hot fire testing. Digital Image Correlation has been investigated and being evaluated as a technique to augment traditional instrumentation during component and engine testing providing further data for additional performance improvements and cost savings. The feasibility of digital image correlation techniques were demonstrated in subscale and full scale hotfire testing. This incorporated a pair of high speed cameras to measure three-dimensional, real-time displacements and strains installed and operated under the extreme environments present on the test stand. The development process, setup and calibrations, data collection, hotfire test data collection and post-test analysis and results are presented in this paper.
Motivation for Technology

- Subscale and Full-scale testing requires expensive and labor intensive instrumentation to better understand hardware performance
  - Design Modifications and Performance Predictions based on “discrete” point instrumentation
    - Thermocouples, Pressure Transducers, Accelerometers, Strain Gages
- **Challenge: Measure highly dynamic elevated temperature components**

Goal: Augment Traditional Gages to gain a better understanding of hardware and environment loads to design more efficient components and systems
Applications and Development work for Digital Image Correlation at NASA

- Blast Pressure Wave Tracking at 70,000 fps
- Subscale Nozzle Displacements at 1700F
- Full-Field Strain and Displacements of 18-ft Dia Tank
  Ref: Todd Boles, MSFC/ET30
- High Speed Composite Compression – Direct Application of Major Strain
  ET (on Pad) Cryo tanking test to observe stringer displacement
- Debris Impact Testing – Eliminated Strain Gages

Test 91  April 3, 2013  300 SS  0.005° Half H2O

Last Frame Before Perforation
Digital Image Correlation - Overview of Technology

- Uses paired high speed video cameras calibrated to a volume to full field surface data
- Post-processing of paired images to determine Displacement of surface, strains, acceleration, velocity
- High Speed cameras can provide high frame rate although frame rate limited by duration of test and current post-processing techniques (tremendous amounts of data)
What is Digital Image Correlation?

Contrasting Pixels applied to part (Speckle Pattern) + Stereo Camera Triangulation = Full Field Displacement and Strain Measurements
PONTOS Lab Experiments

Nozzle Deformation
Date: 4/2/2013
0.000000 sec
Phantom 7.1M HS
50mm lenses

Paul Gradl
Gilbert Handley
ARAMIS Lab Experiments – Displacement

Stage 20

Nozzle Displacement Z

Stage 20
Time 0.23 s
2/22/2013

Displacement Z

[Graph showing displacement over time and space, with sections labeled Section 1 to Section 3.]

Point 1 Displacement

[Graph showing point 1 displacement over time with a peak and a drop.]
ARAMIS Lab Experiments – Principal Strain

Stage 15

Nozzle - Major Strain

Major Strain

Stage 15
Time 0.17 s
2/22/2013

Point 1 - Reference
D +0.0121 in

Stage 15

Time (s)
Subscale Hot-fire Nozzle Testing

Test Photos and Data Collection:
Paul Gradi
Gilbert Handley
Sandy Elam Greene
Bench Testing Doesn’t Always Translate into the Field

Nozzle Extension Skirt Buckling Test
Intentional Predicted Failure
May 22, 2013

Time: 0.000000 s from trigger

Phantom High Speed v7.1M
750 fps
135mm lens @6ft
Motivation to Develop Technique

Stage 0

Nozzle Strain Gage 1

Time 0.000 s
Stage 0

1700F

Subscale Nozzle Hotfire Demonstration
Phantom v7.1 M, 1250 fps

6/13/2013

Paul Gradl
Gilbert Handley
Subscale Hotfire Testing – Data Analysis

![Graph showing predicted and measured radial displacements vs. wall temperature. Predicted radial displacement is plotted as a blue line. Measured with DIC - Test 1 is plotted as red dots, and Measured with DIC - Test 2 is plotted as green dots.](image-url)
Subscale Hotfire Testing – Averaged Data

Optical test data tracking closely with predictions; error grows at elevated temperatures.
Large Scale D.I.C. for Engine Hotfire Testing

MSFC has developed new optical measurement techniques to augment or replace traditional gages in harsh environment engine testing or manufacturing operations.

Stereo high-speed cameras measure full-surface displacements and strains using “speckle pattern” (calibrated triangulation).
- Leveraged basic techniques from NESC Shell Buckling Test and NASA & industry experts.
- Developed speckle pattern and initial vibration damping in subscale hotfire testing at MSFC.
- J-2X provided the test-bed environment to develop camera stability damping.
- Industry-first attempt for high temperature, high vibration environments where traditional gages do not operate reliably.

Stereo Cameras installed and Speckle Pattern Applied at Stennis A1 Stand.

Trial run on J-2X Test A1J026.
ARAMIS high speed cameras

Photo Credit: Dan Goade
Test Data Collection:
Paul Gradl, Gilbert Handley, Brian West
Engine Movement and Strains during Pre-test Ops

Ability to track engine during all chill and gimbal checkout operations
ARAMIS Full Surface Strain Measurement Proof of Concept
Displacement during A1J028 Test

Displacement E (Total X, Y, Z)

ARAMIS Trial on J-2X A1J028

Paul Gradl
Gilbert Handley
Error Associated With Measurements During Hotfire
Demonstrated initial feasibility of using photogrammetry and digital image correlation for range testing of missile burst testing.

Test Support: Paul Gradl/MSFC, Cory Medina/MSFC, John Tyson/Trilion, John "Yanni" Psilopolous/Trilion
Feasibility of 6-dof Analysis of Missile Testing

Test 62 - TM1 Hydra Missile Testing

Test Data provided:
Paul Gradl and Cory Medina
Conclusions and Future Work

NASA MSFC has advanced a series of dynamic digital image correlation techniques for use during hotfire engine testing

- Subscale and full scale testing and analysis has demonstrated feasibility to accurately determine local and global displacements and surface strains

NASA will continue to advance this technology for rocket engine testing, subscale testing, component testing and bench top testing

- Replace traditional measurement systems
- Integrate with modern analysis tools
- Combine advanced techniques such as IR thermography and digital image correlation
- Continue to research and advance techniques for elevated temperature applications

Share lessons learned with industry and government through technical papers and presentations
The possibilities of dynamic data collection are endless...
Dynamic responses require an input to excite the system...
Images were collected using a projected pattern instead of painting a speckle pattern on her belly…

High Speed cameras were post triggered after movements felt.
To ensure that kicks and movement data was real a background test was conducted with no baby movement (to correct for breathing and body motion)
Displacement in Z Axis
Baby Gradl Movement - Shift to Right Side

Time 0.00 seconds
Displacement in Z Axis
Baby Gradl Movement - Baby Kicking
References


Gradl, P.R. “Application of Optical Measurement Techniques during Stages of Pregnancy”. To be published in Summer 2016, TBD.


High Speed Fragmentation Testing

Test 91  April 3, 2013  300 SS 0.005"  Half H2O

Stage 4300
Elapsed Time 122.221930 ms

Displacement Z

Section 0

Stage point 0

Section 1

Stage point 1

Displacement Z [in]

-0.05

0.00

0.05

0.10

0.15

0.20

0.25

0.30

0.35

Section length [in]

0.00

1.50

3.00

4.50

6.00

6.49

[0]

Elapsed Time [ms]

42.5

60.0

80.0

100.0

127.7

Magnified View

[Image of magnified view of test results]

[Color bar indicating displacement range]
High Speed Fragmentation Testing (cont)

Test 93  April 3, 2013  300 SS 0.003"  Full H20

Stage 6483  Time 0.12 s

Displacement Z

- Section 0
- Section 1
- Stage point 0
- Stage point 1

Elapsed Time [ms]

Displacement Z [in]

Section length [in]
Space Launch System (SLS) Debris Impact Testing

Test provided by: Paul Gradl and Cory Medina
Chip Kopicz, Perry Gray, Bart Suggs
SLS RS25 Nozzle Pressurized Panel

SLS RS25 Pressurized Panel Testing
13 Nov 2015; 6# Foam

Displacement Z

Elapsed Time
0.00 ms

Paul Gradl  Cory Medina  Chip Kopicz