Highly Elastic Strain Gage for Low Modulus Materials

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NASA Armstrong Flight Research Center, Edwards CA
Spring WRSGC in San Antonio, TX
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Outline
Background

Need
• Large magnitude strain measurements on highly elastic materials possessing low Young’s modulus and high yield strain (i.e. fabrics, rubbers, elastomers, etc.)

Problem
• Current resistive foil and fiber optic strain gages have limitations
  – Strain range < 20%
  – Localized stiffening due to relatively high modulus of sensor and adhesive

Proposed Solution
• Adapt current Plethysmography liquid metal strain gage technology for aerostructures (current use: testing endothelial dysfunction and reactive hyperemia)
  — Modify system for large strains > 100%
  — Modify sensor physically
  — Calibrate / evaluate to large strains required on aerostructure applications

Potential NASA Projects
• Inflatable reentry TPS concepts
• Gulfstream III ACTE
Plethysmography: testing endothelial dysfunction and reactive hyperemia

Manufacturer (contacted)
D. E. Hokanson, Inc.
12840 NE 21st Place
Bellevue, WA 98005 USA

System
EC6 features include AC and DC coupling, seven range settings, adjustable analog output for use with an external chart recorder, and a built-in RS232 data output.

Liquid Metal Strain Gage

<table>
<thead>
<tr>
<th>Strain Gauge Sets</th>
<th>Sizes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limb</td>
<td>Eight gauges from 22 to 36 cm in 2 cm increments</td>
</tr>
<tr>
<td>Forearm</td>
<td>Eight gauges from 16 to 30 cm in 2 cm increments</td>
</tr>
<tr>
<td>Digit</td>
<td>Seven gauges from 4.5 to 7.5 cm in 0.5 cm increments</td>
</tr>
</tbody>
</table>
The resistance of the mercury in the tube can be measured with a pair of metal electrodes, one at each end. Since mercury is essentially incompressible, forces applied along the length of the tube stretch it, and also cause the diameter of the tube to be reduced, with the net effect of having the volume remain constant. The resistance of the strain gauge is given by

\[ R = \frac{\rho L}{A} = \frac{\rho R^2}{V} \]

where \( \rho \) is resistivity of the mercury, \( L \) is length of the conductive fluid, \( A \) is the cross-sectional area, and \( V \) is the volume. Taking the derivative gives

\[ \frac{dR}{dL} = \frac{2\rho L}{V} = \frac{2R}{L} \]

We define a quantity called the gage factor \( K \) as:

\[ K = \frac{dR/R}{dL/L} \]

Since

\[ \frac{dR}{dL} = \frac{2R}{L} \]

we have \( K = 2 \) for a liquid strain gage.

This means that the fractional change in resistance is twice the fractional change in length. In other words, if a liquid strain gauge is stretched by 1%, its resistance increases by 2%. This is true for all liquid strain gauges, since all that is needed is that the medium be incompressible.

Liquid strain gauges were used in hospitals for measurements of fluctuations in blood pressure. A rubber hose filled with mercury was stretched around a human limb, and the fluctuations in pressure were recorded on strip-chart recorders, and the shape of the pressure pulses could be used to diagnose the condition of the arteries. Such devices have been replaced by solid state strain gauge instruments in modern hospitals, but this example is still interesting to use as an introductory example.

Source: [http://www.stanford.edu/class/me220/data/lectures/lect03/lect_3.html](http://www.stanford.edu/class/me220/data/lectures/lect03/lect_3.html)
Sensor evaluation testing will be performed on liquid metal strain gage (LMSG) for high elastic strain measurement feasibility. Depending on results, further testing will include NASA project related substrates and structures

- Initial tests to be done on moderately elastic materials to enable comparison with foil strain gages and evaluate gage factor (GF), repeatability, scatter, and drift
  - Extensometer hard attach with tensile load (2 pint. w/epoxy)
  - Full sensor bond under with applied bending loads on fiberglass or Plexiglas® (silicone adhesive)
  - Study opening hoop versus folding back on self sensor configurations
  - Characterize resistivity in varying thermal conditions
- If further testing warranted, test materials applicable to HIAD’s and G-III against optical measurements
  - Attach and test on appropriate materials
    - ballute straps provided by LaRC
    - elastomer skin provided by FlexSys Inc. (Ann Arbor, MI) and ATK
**Attachment Procedure**

- Sanded, cleaned/prepped substrate using standard SG procedures
- Encapsulated sensor with minimal taunt using silicone RTV (including end-loop)
- Connected phone jack connected input to EC6 system, adjusted range (0.5%) and balanced
- Recorded millivolt out with laboratory DAS
Initial Evaluation

Current Sensor/System Configuration

- Circumferal type measurement
- Plastic hook at electrical wire and LM silicon tubing interface for arterial Plethysmography measurements (in yellow)
- Liquid metal conductor: Indium-Gallium w/silicon tubing
- Stereo phone jack sensor input to EC6 system, adjustable range and balance (zero)
- Single channel system, millivolt output for recording to DAS
- Max-op strain range of 2% (D.E. Hokanson system limit)

Future Configuration

- Transform to flat axial measurement: smooth/reduce transition from electrical wires to LMSG tubing (hook/plastic interface removed)
- Open strain range to >20% (D.E. Hokanson system mods)
- Attempt to adapt to traditional DAS by Wheatstone bridge or constant current if necessary
- If constant current, replace leadwires with smaller gauge wire since a Kelvin measurement
- Investigate mercury as LM conductor for flight applications (lower melting point temperature)
Modified Sensors Construction

Single Active Liquid Metal Strain Gage - GL - LWL
P# SALMSG-1.25-15

-Ex
+S
-S
-Ex

34 AWG, 4-cond, ribbon cable

≈ 0.7-in

1.25-in

Solder tinned twisted pair

Silicon Tubing
OD = 0.042"

Cu Wire
L = 0.3”; Dia. = 0.033”

Solder connection

Shrink sleeve

Indium-Gallium filled
Sensor Configuration for Proposed Temperature-Compensated LMSG for Flight Applications

Active Gage ($\varepsilon_1$) = applied mechanical strain ($\varepsilon_{M1}$) + strain due to temperature change ($\varepsilon_{T1}$)

Dummy ($\varepsilon_2$) = strain due to temperature change ($\varepsilon_{T2}$)

Assume $\varepsilon_{T1} \approx \varepsilon_{T2}$

Therefore

$\varepsilon_1 - \varepsilon_2 = \varepsilon_{M1}$
Modified Sensors Construction

WAS

Silicon Tube

Copper Rods

4 Cond. Ribbon Wire
Installation Procedures

Stake-Down tools used to position sensor in adhesive and keep transverse sensitivity consistent between install
Installation Procedures

1. Layout, mask, roughen, & clean
2. Position sensor and stake-down
3. Hook sensor and verify resistance using Kelvin measurement; desired range 0.08, ±0.005Ω
4. Apply silicon adhesive to substrate; use heavier application on Cu elements
5. Weigh down Cu elements if possible
6. Remove masking check resistance

7. Procedure later modified to not encapsulate silicon tube and install in thin silicon bed (reduce stiffing)
8. Encapsulate only ½ of Cu elements
LMSG Signal Conditioning

Card configured for single-active gage (no temp-comp)

Active Leg

Comp. Leg (when used)

1st Stage Amp

2nd Stage Subtraction
# Coefficient and Gage Factor (GF)

<table>
<thead>
<tr>
<th>Signal Conditioning Gain (Av)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Amp Gain = 50K/RG</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st Stage IN</td>
<td>0.00747</td>
<td>OUT</td>
<td>1.8475</td>
<td>247.32</td>
</tr>
<tr>
<td>2nd Stage IN</td>
<td>0.0324</td>
<td>OUT</td>
<td>0.349</td>
<td>10.77</td>
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<tr>
<td>Total AV</td>
<td>Stage 1*Stage 2</td>
<td>2664.06</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Ri**: Initial sensor resistance (Ω)
- **ΔR**: change in sensor resistance (Ω)
- **Vo**: voltage out (V)
- **I**: current (mA)

**GAGE FACTOR (GF)**

\[ GF = \frac{ΔR}{R_i} \]

**COEFFICIENT (Coe)**

\[ Coe = \frac{1}{(I*R_i*Gain)} \]

**STRAIN (ε)**

\[ ε = Coe*Vo*GF' \]

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**Constant Current PCB**

**ARMSTRONG FLIGHT RESEARCH CENTER**
### Laboratory Cantilever Testing

#### Plexiglass Bending Beam

<table>
<thead>
<tr>
<th>Description</th>
<th>Weight (lbs)</th>
<th>Strain (ue)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leveled from ground (zeroed)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Clamps / Bracket (0.6lb)</td>
<td>0.6</td>
<td>1520</td>
</tr>
<tr>
<td>C&amp;B (0.6ibs) / holder (1lb)</td>
<td>1.6</td>
<td>3460</td>
</tr>
<tr>
<td>C&amp;B (0.6ibs) / holder (1lb) / weights (1.5lb)</td>
<td>3.1</td>
<td>5140</td>
</tr>
<tr>
<td>Leveled from ground</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Plexiglass Substrate**
Laboratory Cantilever Testing
Plexiglass Bending Beam

\[ \varepsilon = \text{Coe} \times V_{\text{out}} \times GF' \]

Coe = \frac{1}{(I \times R_i \times \text{Gain})}

\[ I = 0.1 \]
Kelvin
\[ R_i = 0.077, 0.076, 0.075, 0.079 \]

Gain 2664.062

GF' = 0.27

<table>
<thead>
<tr>
<th>Strain (ue)</th>
<th>Strain (ue)</th>
<th>LMSG5</th>
<th>LMSG6</th>
<th>LMSG7</th>
<th>LMSG8</th>
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</thead>
<tbody>
<tr>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>1550</td>
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<td>5000</td>
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<td>26</td>
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<table>
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<tr>
<th>Strain (ue)</th>
<th>Strain (ue)</th>
<th>LMSG5</th>
<th>LMSG6</th>
<th>LMSG7</th>
<th>LMSG8</th>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>-41</td>
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<table>
<thead>
<tr>
<th>Weight (lbs)</th>
<th>Strain (ue)</th>
<th>LMSG5a</th>
<th>LMSG6a</th>
<th>LMSG7a</th>
<th>LMSG8a</th>
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<td>0</td>
<td>0</td>
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<td>0.6</td>
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<td>1539</td>
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<td>3614</td>
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<td>0</td>
<td>-39</td>
<td>-13</td>
<td>14</td>
<td>-38</td>
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</tbody>
</table>

**3rd Load Cycle**
- Constant "I" Circuit
- Coe adjusted for Ri
- GF' = 0.27
- Install tool and bottom adhesive attachment
Laboratory Cantilever Testing

Fiber Glass Bending Beam

Strain (µε)

Load (lbs.)

LMSG vs SG on Fiberglass Bending Beam

SG Ave (C1)
LMSG2 x (C1)
Laboratory Tensile Testing

Graphite Epoxy Tensile Bar

HOOK

| \( \sigma = \varepsilon E \) and \( \sigma = F/A \) |
|---|---|
| \( F/A = \varepsilon E \) »» \( F = \varepsilon AE \) |

where

- \( \sigma \): stress
- \( \varepsilon \): strain
- \( F \): force (lbs)
- \( E \): modulus (psi)
- \( A \): area (W”*H”)
- \( \varepsilon \): Increment 0.001
- \( X \): X
- \( 6000000 \):
- \( 1.1 \): 0.192
- \( 0.2112 \): 0.869
- \( 0.0814 \):

\( F/1000\varepsilon\mu = 1267.2 \text{ lbs} \)
Laboratory Tensile Testing
Graphite Epoxy

\[ \varepsilon = \text{Coe} \times \text{Vout} \times \text{GF}' \]
\[ \text{Coe} = \frac{1}{\text{I} \times \text{Rinital} \times \text{Gain}} \]
\[ \text{I} = 0.1 \]
\[ \text{Gain} = 2664.061596 \]
\[ \text{GF}' = 0.51 \]
\[ \text{Ri} = 0.0869 \quad 0.0814 \]

<table>
<thead>
<tr>
<th>Load (lbs)</th>
<th>SG1</th>
<th>LMSG1</th>
<th>LMSG2</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>1267</td>
<td>975</td>
<td>1053</td>
<td>1087</td>
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<tr>
<td>2534</td>
<td>1940</td>
<td>1978</td>
<td>2037</td>
</tr>
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<td>3802</td>
<td>2909</td>
<td>2862</td>
<td>2954</td>
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<td>3741</td>
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<td>6336</td>
<td>4798</td>
<td>4703</td>
<td>4802</td>
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<td>5069</td>
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<td>3742</td>
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<tr>
<td>3802</td>
<td>2928</td>
<td>2685</td>
<td>2780</td>
</tr>
<tr>
<td>2534</td>
<td>1961</td>
<td>1557</td>
<td>1776</td>
</tr>
<tr>
<td>1267</td>
<td>977</td>
<td>681</td>
<td>840</td>
</tr>
<tr>
<td>0</td>
<td>35</td>
<td>-59</td>
<td>0</td>
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</table>

LMSG vs SG
Composite Tensile Coupon

Slight non-linear return
HIAD Torus Testing
Hypersonic Inflatable Aerodynamic Decelerator

Test Overview
• Six Tori were tested (from LaRC / UMaine)
• Kevlar reinforced rubber
• Tori diameters ranged from 11 to 14.5-ft
• Compression and torsion loads applied to cause in-plane and out-of-plane buckling
• Data used to improve failure models (takes no more load w/runaway displacements)

Instrumentation
• Eight string pots and 16 LRTs
• 64 load cells (16 controllers)
• Two photogrammetry systems:
  — ARIMIS (strain)
  — PONTOS (target displacement)
• 16 LMSGs per torus

http://www.nasa.gov/centers/armstrong/Features/HIAD_decelerator_system.html
HIAD Torus Installation

LMSGs
- High strains were not required (10,000 με), but structure possessed low elastic modulus
- Eight sensors on each upper and lower cord
- Measured strain to buckle (failure)
- Strains matched well with PONTOS Photogrammetry system
Elastomer Testing

Current AFRC Elastomer Projects
- NASA / AFRL Adaptive Compliant Trailing Edge
- AFRC CIF "Fundamental Research into Hyperelastic Materials for Flight Applications" – PI Eric Miller

GL determined using Aramis for coefficient

- Load was stopped approximate at doubling of GL using scale real-time
- Post test photogrammetry data was used to precisely determine strain at center of coupon
- Determined prelim strain coefficient: \( y = 85804x \)
- LMSG slightly non-linear, second order poly will be determined and applied after first coupon
• Slightly different strain value when using the graphics vs. displacement output
• During these tests stiffening was minimized to be negligible
Observations from elastomer testing

- Cycle-to-cycle repeatability was excellent though gage-to-gage scatter was 5-6%
- Coefficient changed slightly over time, believed to be changes in bond at fixation
- Though direct bond fixation better than grips, true strain with photogrammetry more actuate than measured $\Delta L$ when determining GF

<table>
<thead>
<tr>
<th>Nominal Strain</th>
<th>LMSG 1 (ΔL)</th>
<th>LMSG 2 (ΔL)</th>
<th>LMSG 1 GF</th>
<th>LMSG 2 GF</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.0919</td>
<td>0.0862</td>
<td>2.10</td>
<td>2.00</td>
</tr>
<tr>
<td>1</td>
<td>0.2288</td>
<td>0.2170</td>
<td>2.61</td>
<td>2.52</td>
</tr>
<tr>
<td>Initial R</td>
<td>0.0875</td>
<td>0.0862</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### LMSG RT Elastomer Tensile Test

**24-in Caliper**
- Dow Corning 3145 bond to caliper
- Power supply to constant current PCB: 15VDC @ 0.208A
- Coe: 105000

#### Consecutive Tensile Loads to 100% Strain

Both gages repeated within ±1.5%

---

**Elastomer Tensile Testing**

**Length Based with Caliper**

#### Start L = 6.250 in

<table>
<thead>
<tr>
<th>% Strain</th>
<th>Delta (in) Nominal</th>
<th>Delta (in) Actual</th>
<th>LMSG 1</th>
<th>LMSG 2</th>
<th>Dev Gage-to-Gage</th>
<th>Dev Repeatability</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0 (Zeroed)</td>
<td>0.000</td>
<td>0</td>
<td>0</td>
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<tr>
<td>16</td>
<td>1</td>
<td>1.001</td>
<td>119,876</td>
<td>112,150</td>
<td>6.44%</td>
<td>-0.21% -0.08%</td>
</tr>
<tr>
<td>32</td>
<td>2</td>
<td>2.003</td>
<td>256,520</td>
<td>239,990</td>
<td>6.44%</td>
<td>-0.29% -0.24%</td>
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<tr>
<td>48</td>
<td>3</td>
<td>3.000</td>
<td>409,390</td>
<td>383,000</td>
<td>6.45%</td>
<td>-0.45% -0.54%</td>
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<tr>
<td>64</td>
<td>4</td>
<td>4.000</td>
<td>583,150</td>
<td>546,180</td>
<td>6.34%</td>
<td>0.04% 0.02%</td>
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<tr>
<td>80</td>
<td>5</td>
<td>5.005</td>
<td>781,290</td>
<td>734,320</td>
<td>6.01%</td>
<td>0.01% -0.09%</td>
</tr>
<tr>
<td>96</td>
<td>6</td>
<td>5.998</td>
<td>995,940</td>
<td>942,420</td>
<td>5.37%</td>
<td>-0.68% -0.84%</td>
</tr>
<tr>
<td>100</td>
<td>6.25</td>
<td>6.251</td>
<td>1,069,280</td>
<td>1,010,720</td>
<td>5.48%</td>
<td>-0.05% -0.23%</td>
</tr>
<tr>
<td>96</td>
<td>6</td>
<td>5.999</td>
<td>998,900</td>
<td>943,850</td>
<td>5.51%</td>
<td>-0.23% -0.44%</td>
</tr>
<tr>
<td>80</td>
<td>5</td>
<td>5.005</td>
<td>781,370</td>
<td>734,150</td>
<td>6.04%</td>
<td>-0.29% -0.43%</td>
</tr>
<tr>
<td>64</td>
<td>4</td>
<td>3.999</td>
<td>584,700</td>
<td>547,000</td>
<td>6.45%</td>
<td>-0.29% -0.43%</td>
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<tr>
<td>48</td>
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<td>2.996</td>
<td>409,820</td>
<td>382,640</td>
<td>6.63%</td>
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<tr>
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<td>2.006</td>
<td>256,990</td>
<td>239,460</td>
<td>6.82%</td>
<td>-0.03% -0.32%</td>
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<tr>
<td>16</td>
<td>1</td>
<td>0.999</td>
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<td>110,850</td>
<td>6.97%</td>
<td>-0.72% -1.47%</td>
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<tr>
<td>0</td>
<td>0</td>
<td>0.000</td>
<td>-550</td>
<td>-700</td>
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<td></td>
</tr>
</tbody>
</table>

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**Strain ($\mu\varepsilon$)**

<table>
<thead>
<tr>
<th>Percent Strain</th>
<th>Dev gage-to-gage</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.000</td>
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<tr>
<td>1</td>
<td>0.000</td>
</tr>
<tr>
<td>2</td>
<td>0.000</td>
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<tr>
<td>3</td>
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<td>8</td>
<td>0.000</td>
</tr>
<tr>
<td>9</td>
<td>0.000</td>
</tr>
<tr>
<td>10</td>
<td>0.000</td>
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</tbody>
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**Percent Strain vs. Strain (με)**

- LMSG 1
- LMSG 2
- Dev gage-to-gage
Summary

- Successfully adapted current Plethysmography liquid metal strain gage technology for Aerostructures
  - Highly elastic strain sensor (>100%), negligible stiffening
  - In-house designed signal conditioning
  - Excellent repeatability
  - Good scatter
  - If photogrammetry tests confirm nonlinearity, 2nd order poly will be used
- Sensor and leadwire attachments developed
  - Initial resistance critical, devised stake-down tool
  - Minimal base adhesive used to minimize local stiffening (do not encapsulate)
  - Leadwire handling critical in avoiding unwanted induced strains
- LMSGs successfully used during HIADs testing on Kevlar enforce rubber substrate (seven tori instrumented with 16 LMSGs each)
- Completion of photogrammetry evaluation and maximum strain testing to be accomplished in near-future