Ultrasonic Thermometry for Recession Measurements in Ablative Materials

5th Ablation Workshop: University of Kentucky: February 28, to March 1 2012
Joseph A. Lloyd and Donald E. Yuhas, PhD.
Outline

• Background of Ultrasonic Thermometry

• Applications
  – Regenerative Combustors
  – Extreme Temperature
  – Thermal gradients

• Re-Entry Applications:
  – Challenges
  – Recession Measurement Concept
  – Scoping studies
Background

- Auto ignition or “cook-off” is one of the most serious safety concerns when firing large caliber guns.
- NETS - Non-intrusive Erosion & Temperature Sensor
Background

Key Components

- Ultrasonic Sensors
- High Speed Data Acquisition
- High Bandwidth Ultrasonic Instrumentation
- High Speed Data transfer/Storage
- Independent Temperature Sensor /Normalization
- Cooperative/Characterized Materials
- Relevant Property Data over Operating Range
Background

Overarching integral relationship:

\[ G = 2 \int_0^L \frac{1}{V(T(x))} \, dx \approx \frac{2}{V_0} \int_0^L [1 + \xi \theta(x)] \, dx \]

\( G \) = Ultrasonic ToF

\( L \) = Length of Propagation

\( \xi \) = Velocity-Expansion coefficient

\( V_0 \) = Velocity of Sound at reference temperature \( T_0 \)

\( \theta(x) = T(x) - T_0 \)

Under isothermal thermal conditions, \( \frac{\Delta G}{G} = \xi (T - T_0) \)
Background: Localization

Layered Structural Echoes

Step Structural Echoes

Backscatter Structural Echoes
Propulsion Applications

1 JP-10 @ 1000psi pulse-echo

- Amplitude (volts)
- Time (microseconds)

- 95C
- 22C
Propulsion Applications

\[ \Delta G/G \text{ vs. Temperature for JP-10} \]
(1000 Psi)

\[ y = 2.21 \times 10^{-3} x - 5.59 \times 10^{-2} \]
Extreme Temperatures

![Graph of Alumina Temperature vs. Fractional TOF (DG/G) with experimental and book data points]

- Experimental Data
- Book Data

![Image of extreme temperature experiment]
Backscatter: Copper
Backscatter: Copper

a) Copper Rod

Grain Backscatter

Transducer

Heat Source

b) Acoustic Wave Trace Divided into 15 2usec Windows (Copper)

C)

3D Top Map of Travel Time Change

Temperature (°C):

25°C  80°C  150°C  200°C
Inversion and Heat Flux

Flowchart:
- Forward Conduction Solution
  - Approximate Boundary Condition
    - Adjust Boundary Condition
      - Exact Boundary Condition
  - Temperature Distribution
    - Predict ToF
      - Compare Predicted With Real
        - Yes: Correct Temperature Distribution
          - Does Approximate Boundary Condition Work
            - No: Adjust Boundary Condition
            - Yes: Correct Temperature Distribution

Heating Profile:
- $T_0$
- $T_1$
- $T_2$

Heat Source On
Re-Entry Applications
Re-Entry Applications

Challenges:

High Attenuation

Significant Backscatter

Anisotropy

Recession/Temperature
Anisotropy

Re-Entry Applications:

![Diagram showing anisotropy with axes 1, 2, and 3]

![Bar chart titled "Carbon Phenolic 1" showing velocities V11, V22, V33, V31, and V32]
Re-Entry Applications

Velocity

<table>
<thead>
<tr>
<th>Mode</th>
<th>V11</th>
<th>V22</th>
<th>V33</th>
<th>V13</th>
<th>V31</th>
<th>V12</th>
<th>V21</th>
<th>V32</th>
<th>V23</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity</td>
<td>5.0</td>
<td>0.0</td>
<td>1.0</td>
<td>2.0</td>
<td>2.5</td>
<td>0.5</td>
<td>1.5</td>
<td>2.0</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Carbon Phenolic 2

Signal Loss

<table>
<thead>
<tr>
<th>Mode</th>
<th>V11</th>
<th>V22</th>
<th>V33</th>
<th>V13</th>
<th>V31</th>
<th>V12</th>
<th>V21</th>
<th>V32</th>
<th>V23</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal Loss</td>
<td>0.5</td>
<td>0.5</td>
<td>1.5</td>
<td>1.0</td>
<td>1.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Re-Entry Applications

Recession Measurement Concept

\[ \Delta G(t) = \left[ \frac{\partial G}{\partial L} \right] \Delta L(t) + \left[ \frac{\partial G}{\partial \theta} \right] \langle \Delta \theta(t) \rangle \]

- Determine frequency & configuration
- Understand echo origin & Measure ultrasonic properties
- Track & measure \( \Delta G \) for eroding surface
- Use non-eroding, internal, backscatter echoes to estimate temperature and material property effects
Re-Entry Applications

TC3

Heating source

TC2

Trans  Rec

Amplitude (volts)

Time (microseconds)

echo1  echo2  echo3
Re-Entry Applications
Summary

- **Ultrasonic Thermometry:**
  - Model-independent local temperature measurement
  - Only material property needed for temperature measurement is the Velocity-Expansion Coefficient
  - Material structure becomes the sensor
    - Non-destructive, Non-Intrusive
    - Remote mounting away from harsh, chemically reactive environments
    - Does not disrupt thermal transport
    - Rapid Response
  - Backscatter useful for correcting recession data.
Next Steps

- Continue Scoping Experiments
- Velocity-expansion Coefficient
- Real-time Studies
- Backscatter Temperature Analysis
- Need Teaming Partners for Phase II programs
ACKNOWLEDGEMENTS:

Co-conspirators
Mark Mutton, Jack Remiasz, Carol Vorres    IMS Inc.
Dr. Joseph Koo                        University of Texas
Dr. Greg Walker and Michael Myers       Vanderbilt University

Sponsors & Supporters

Dr. Chuck Boyer (NAVSEA)
Dr. Douglas Talley (Edwards AFB)
Dr. Michael Kendra (AFOSR)
Dr. Ruth Sikorski (AFRL)
Mr. John Feie (AFRL)
Mr. David Adamczak (AFRL)
Capt. John Heaton (AFRL)
Dr. Mairead Stackpoole (ERC Inc.)
Dr. Martin Bacigalupo (BAE)
INDUSTRIAL MEASUREMENT SYSTEMS, INC.

Back-up Slides
Background

• Maximum probe operation: ~500°C
  – But probes can be mounted remotely
• Fast Response: 5000Hz
  – 50 kHz under development
• Heat Flux measurement not limited by thermal mass
  – 2 - 170,000 KW/m² have been demonstrated to date
Background

• Maximum probe operation: ~500°C
  – But probes can be mounted remotely
• Fast Response: 5000Hz
  – 50 kHz under development
• Heat Flux measurement not limited by thermal mass
  – 2 - 170,000 KW/m² have been demonstrated to date
Instrumentation
One Dimensional Model & Heat Flux

\[
G = \frac{2}{v_0} \int_0^L [1 + \xi \theta(x)] \, dx.
\]

\[
G = \frac{2L}{v_0} + \frac{2\xi}{v_0} \int_0^L \theta(x) \, dx.
\]

\[
q''(x = 0) = \rho c_p \int_0^L \frac{\partial \theta (x)}{\partial t} \, dx + q''(x = L).
\]

\[
q''_0 = \frac{\rho c_p}{\Delta t} \int_0^L \Delta \theta(x) \, dx + q''_L,
\]
SIGNIFICANCE OF \( \Delta G \)

\[
q_0'' = \frac{\rho c_p}{\Delta t} \frac{c_0 \Delta G}{2 \xi} + q_L''.
\]

\[
q_0'' = \frac{L \rho c_p}{\xi} \left( \frac{\Delta G}{G_0} \right) \frac{1}{\Delta t} + q_L''.
\]

Change in the time-of-flight from one pulse to the next is really a measure of the stored energy in the system.
Contact

Donald E. Yuhas
DYuhas@imsysinc.com
(630) 236-5901

INDUSTRIAL MEASUREMENT SYSTEMS, INC.
2760 Beverly Drive #4
Aurora, IL 60502
www.imsysinc.com