Ultrasonic Thermometry for Recession Measurements in Ablative Materials

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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)

\[ y = 2.21E-03x - 5.59E-02 \]

Temperature (C)

\[ \Delta G/G \]

0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

0 50 100 150 200 250 300
Extreme Temperatures

Alumina

Temperature (deg. C)

Fractional TOF (DG/G)

Exp. Data
Book Data
Backscatter: Copper
Backscatter: Copper

a) Copper Rod

Grain Backscatter

Heat Source

75mm Region of Interest

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

C)

3D Top Map of Transit Time Change

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

Forward Conduction Solution

Approximate Boundary Condition

Adjust Boundary Condition

Temperature Distribution

Predict ToF

Compare Predicted With Real

Does Approximate Boundary Condition Work

No

Yes

Correct Temperature Distribution

Heat Source On

Heating Profile

$T_0$

$T_1$

$T_2$
Re-Entry Applications
Re-Entry Applications

Challenges:

- High Attenuation
- Significant Backscatter
- Anisotropy
- Recession/Temperature

![Baseline C/C composites graph]

Backwall Echo
Internal Echoes
Anisotropy
Re-Entry Applications:

Carbon Phenolic 1
Re-Entry Applications

**Velocity**

- V11, V22, V33, V13, V31, V12, V21, V32, V23

**Carbon Phenolic 2**

**Signal Loss**

- V11, V22, V33, V13, V31, V12, V21, V32, V23
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)
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
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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

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Instrumentation
One Dimensional Model & Heat Flux

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

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

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

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

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

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

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