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
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

Transducer → Sound Propagation → Echo Returns → Back Wall

Transducer → Sound Propagation → Echo Returns → Step Wall

Transducer → Sound Propagation → Echo Returns → Grain Backscatter

Localisation Region
Propulsion Applications
Propulsion Applications

ΔG/G vs. Temperature for JP-10 (1000 Psi)

The graph shows the relationship between ΔG/G and temperature in degrees Celsius. The equation of the line is given as:

y = 2.21E-03x - 5.59E-02

where y represents ΔG/G and x represents temperature in degrees Celsius.
Extreme Temperatures

![Graph showing temperature vs. fractional TOF (DG/G)]

- **Alumina**
- **Temperature (deg. C):**
  - Exp. Data
  - Book Data

![Images of materials being heated under extreme conditions]

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WWW.IMSYSINC.COM
Backscatter: Copper
Backscatter: Copper

a) Copper Rod

Grain Backscatter

Heat Source

Transducer

75mm Region of Interest

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

C)

3D Top Map of Travel Time Change

Backscatter: Copper

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

- Forward Conduction Solution
- Temperature Distribution
- Predict ToF
- Compare Predicted With Real
- Does Approximate Boundary Condition Work
- Correct Temperature Distribution
- Heat Source On
- Approximate Boundary Condition
- Adjust Boundary Condition

Heat Source

Parameters:
- $T_0$
- $T_1$
- $T_2$
Re-Entry Applications
Re-Entry Applications

Challenges:

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

Re-Entry Applications:

![Diagram](image)
Re-Entry Applications

Velocity

Carbon Phenolic 2

Signal Loss

Velocity

Mode

V11 V22 V33 V13 V31 V12 V21 V32 V23

Signal Loss

Mode

V11 V22 V33 V13 V31 V12 V21 V32 V23
Re-Entry Applications

Recession Measurement Concept

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

- 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

2

1

0

-1

-2

-3

0 50 100 150 200
Re-Entry Applications

Graph 1: dTOF (sec) vs. Temperature (°C) vs. Clock time (sec)

Graph 2: dG3/G3 vs. Temperature (°C) vs. Clock Time (seconds)
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

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

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

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

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

$$q''_0 = \frac{\rho c_p}{\Delta t} \frac{c_0 \Delta G}{2 \xi} + q''_L.$$  

$$q''_0 = \frac{L \rho c_p}{\xi} \left( \frac{\Delta G}{G_o} \right) \frac{1}{\Delta t} + q''_L.$$  

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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