Thermal Measurement of harsh environments using indirect acoustic pyrometry

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Ultrasonic temperature measurement

- Ultrasonics are fairly mature technology
  - Non-destructive evaluation
  - Average temperature measurement of gases, fluids and extrusions
  - Steady temperature distribution (Wadley, 1986 and Berryman, 1990)

- But have not been used in transient heat flux measurement
  - Instabilities of combustion chambers
  - Unstable flows in aerospace applications
  - Internal gun barrel temperatures during firing

- Advantages
  - Remote/non-intrusive measurement
  - Unlike inverse solutions, entire temperature distribution is sampled
  - Leverage existing data acquisition and acoustic technologies
  - Multiple reflection points increases amount of data and improves estimates
Problem/Tests

Cook-off

Live test on MK45 Mod 4 (NSWC)
• Navy Gun with rifling

- time of flight $G(t)$ is a function of temperature
- over rifling step assume temperature is constant $T_r$

$$G(t) = \frac{2}{V_o} \int_0^L \frac{dx}{1 - PT(x, t)} \quad \Rightarrow \quad \Delta G(t) \approx \frac{1}{V_o(1 - P\Delta T_r)}$$
Ultrasonic data reduction—single pulse

- Use **inverse approach** to estimate internal heat flux and temperature
  - Forward model: semi-infinite slab solution for constant interior heat flux (and Duhamel’s theorem) \( q_i \rightarrow \theta_i \)
  - Acoustic model:
    \[
    G_i = \frac{2}{V_o} \int_0^L \frac{dx}{1 - P\theta_i(x, t)}
    \]
  - Inverse model: Adjust \( q_i \) such that estimated and measured \( G_i \) match (function specification with future times)

- **Why would we do this?**
  - For short times, the temperature across the rifling is not constant
  - For applications where the rifling is not available

- **Issues?**
  - Change in time of flight is small, so noise may be an issue
  - The acoustic wave samples the entire temperature distribution not a single point, so the validity of traditional inverse methods is questionable.
Test cases—Exact data

- Time of flight (TOF) was calculated from exact temperature solution
- Red: square flux; Green: triangle; Blue: reverse sawtooth

Normally distributed random noise with a magnitude commensurate with measured time of flights was added to TOF signal.
Test case estimates

a) exact matching; b) 1 future time; c) 4 future times
Test case errors

- Observations
  - reverse sawtooth has largest RMS errors and misses the peak flux
  - no future times (exact matching) captures peak best except for square flux
  - “best” RMS estimate provided with 2 future times
Gun test

Temperature

Heat flux

Crude estimate of heat flux Based on charge and projectile parameters with frictional heating puts the peak heat flux near $117 \text{ MW/m}^2$. 
Conclusions

- Estimation of heat fluxes on inside surface of a gun barrel during a firing event is successful.
- **The time of flight measurement is proportional to heat flux, not temperature, therefore, the inversion is inherently more stable.**

What more do we need to test?
- Well-controlled lab tests
- Incorporate extra pulse as a separate data point
- Are other inversion schemes better for this type of problem
- Effects of sample rate
Gun parameters

- Approximate integral of heat flux estimate

\[ E_b = A \int q''(t) \, dt \approx (3.83 \, m^2) \left[ \frac{1}{2} (125 \, \text{MW/m}^2) (0.1 \, \text{s}) \right] = 23.9 \, \text{MJ} \]

- Energy in propellant for 7 kg charge

\[ E_c(7 \, \text{kg}) \approx 33.1 \, \text{MJ} \]

- Energy in projectile

\[ E_p = \frac{1}{2} m_p v^2 = \frac{1}{2} (31 \, \text{kg})(831 \, \text{m/s})^2 = 10.7 \, \text{MJ} \]

- Gun efficiency

\[ \eta = \frac{E_p}{E_c} \approx 32.3\% \]

- Energy into barrel

\[ E_b = E_c(1 - \eta) \approx 22.4 \, \text{MJ} \]