Thermal Measurement of harsh environments using indirect acoustic pyrometry

November 13, 2007

IMECE

P.L. Schmidt, University of North Carolina, Charlotte
D.G. Walker, Vanderbilt University
D. Yuhas, Industrial Measurement Systems
M. Mutton, Industrial Measurement Systems

This work was supported in part by AFOSR (contract # FA9550-06-C-0071)

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

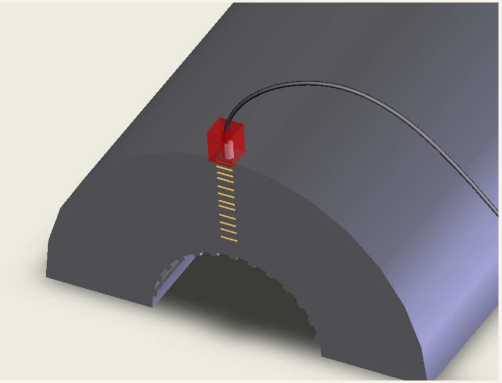
Problem/Tests

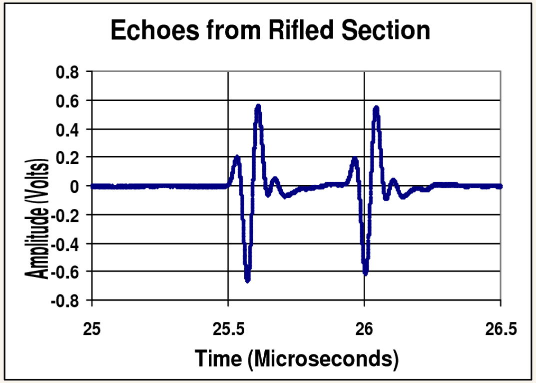
Cook-off

Live test on MK45 Mod 4 (NSWC)

Ultrasonic data reduction—with interface

- **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

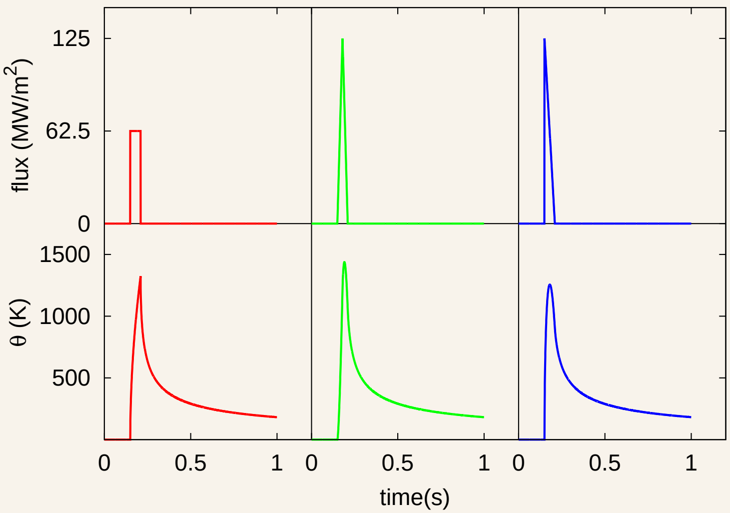
- Use **inverse approach** to estimate internal heat flux and temperature
  - Forward model: semi-infinite slab solution for constant interior heat flux (and Duhamel's theorem) $q_i \rightarrow \theta_i$
  - Acoustic model:

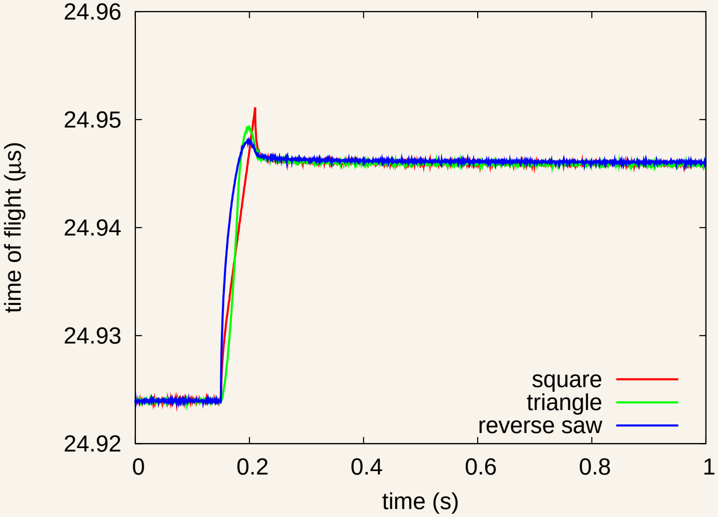
$$G_i = \frac{2}{V_o} \int_0^L \frac{dx}{1 - P\theta_i(x,t)}$$

  - 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

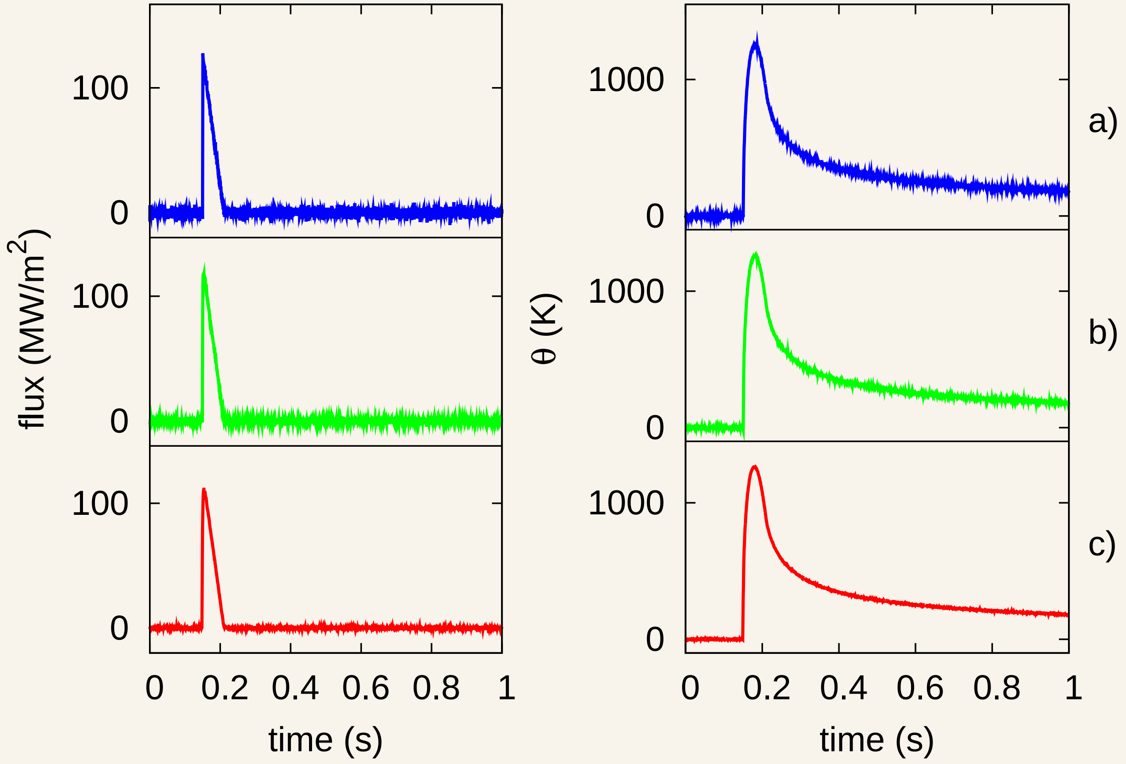
- Time of flight (TOF) was calculated from exact temperature solution
- Red: square flux; Green: triangle; Blue: reverse sawtooth





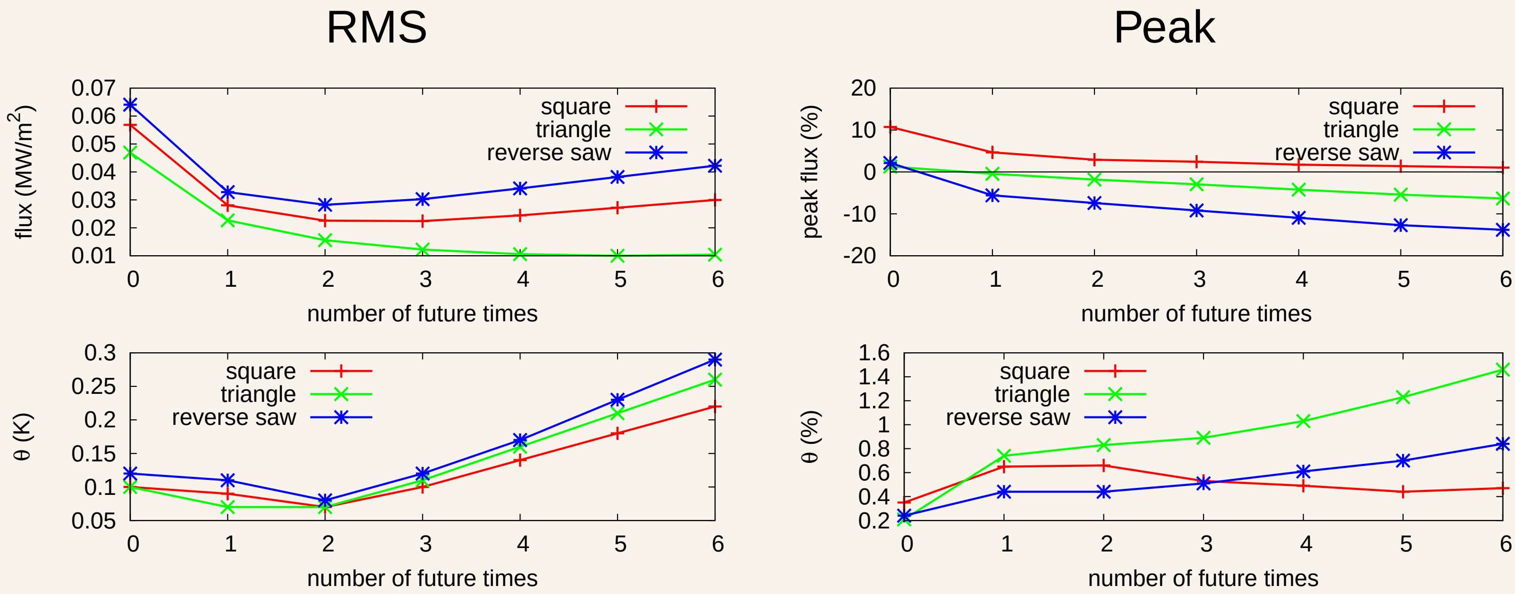
Normally distributed random noise with a magnitude commensurate with measured time of flights was added to TOF signal.

Test case estimates



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

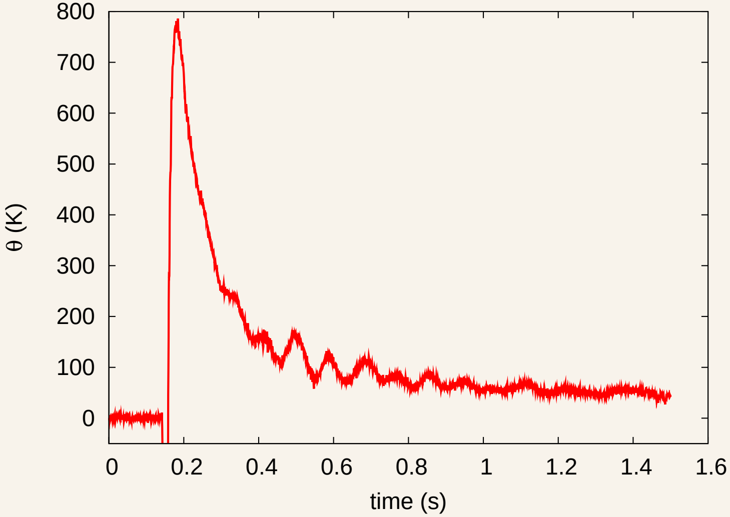
Test case errors



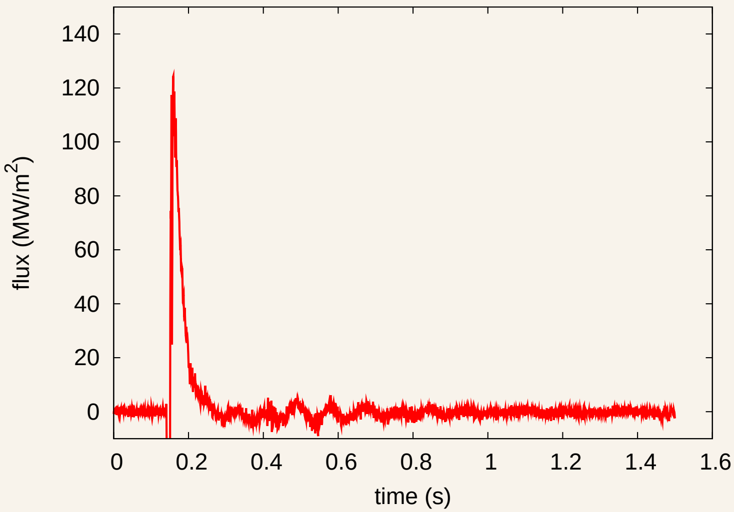
- **Observations**
  - reverse sawtooth has largest RMS errors and misses the peak flux
  - no future times (exact matching) captures peak best except for square flux
  - “best” RMS estimate provided with 2 future times

Gun test

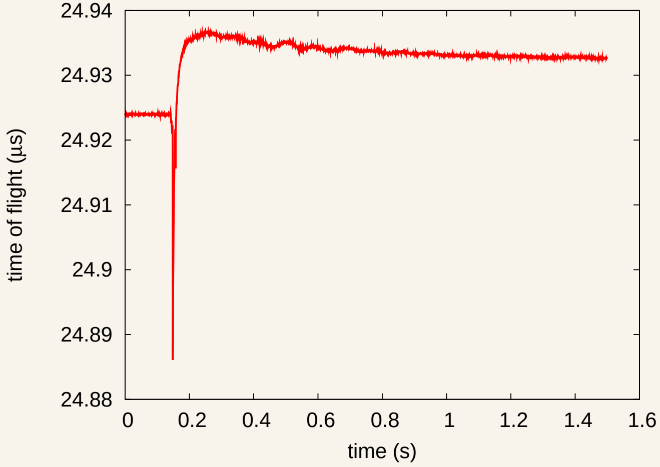
Temperature



Heat flux



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



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

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

- Energy in propellant for $7\,\mathrm{kg}$ charge

$$E_c(7\,\mathrm{kg}) \approx 33.1\,\mathrm{MJ}$$

- Energy in projectile

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

- Gun efficiency

$$\eta = E_p/E_c \approx 32.3\%$$

- Energy into barrel

$$E_b = E_c(1-\eta) \approx 22.4\,\mathrm{MJ}$$