Thermal Measurement of harsh environments using indirect acoustic pyrometry

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IMECE

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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

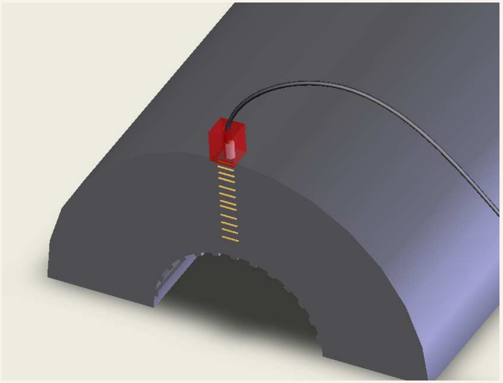
Problem/Tests

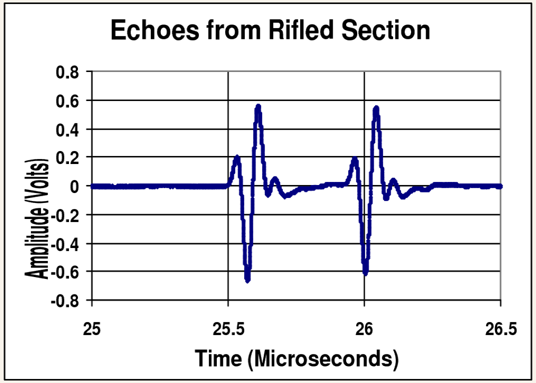
Cook-off

Live test on MK45 Mod 4 (NSWC)

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

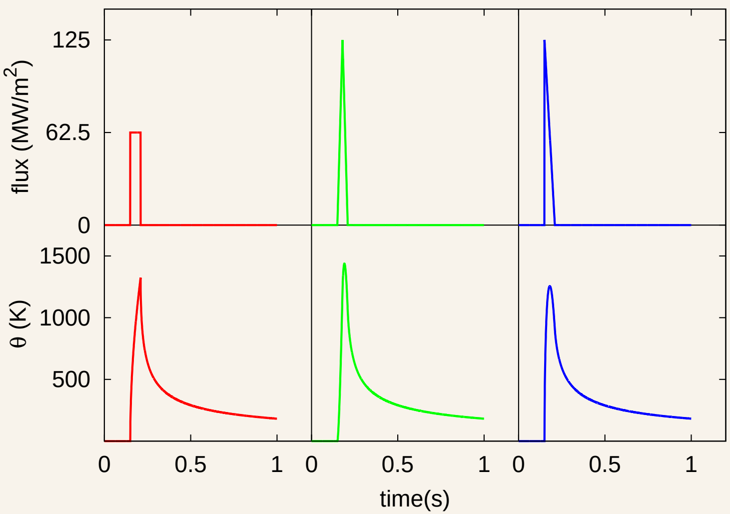
- Use **inverse approach** to estimate internal heat flux and temperature
  - Forward model: semi-infinite slab solution for constant interior heat flux (and Duhamel's theorem) $q_i \rightarrow \theta_i$
  - Acoustic model:

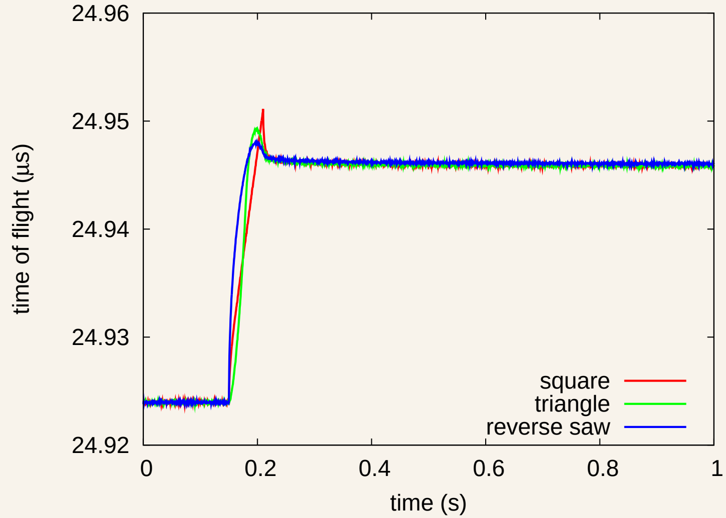
$$G_i = \frac{2}{V_o} \int_0^L \frac{dx}{1 - P\theta_i(x,t)}$$

  - 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

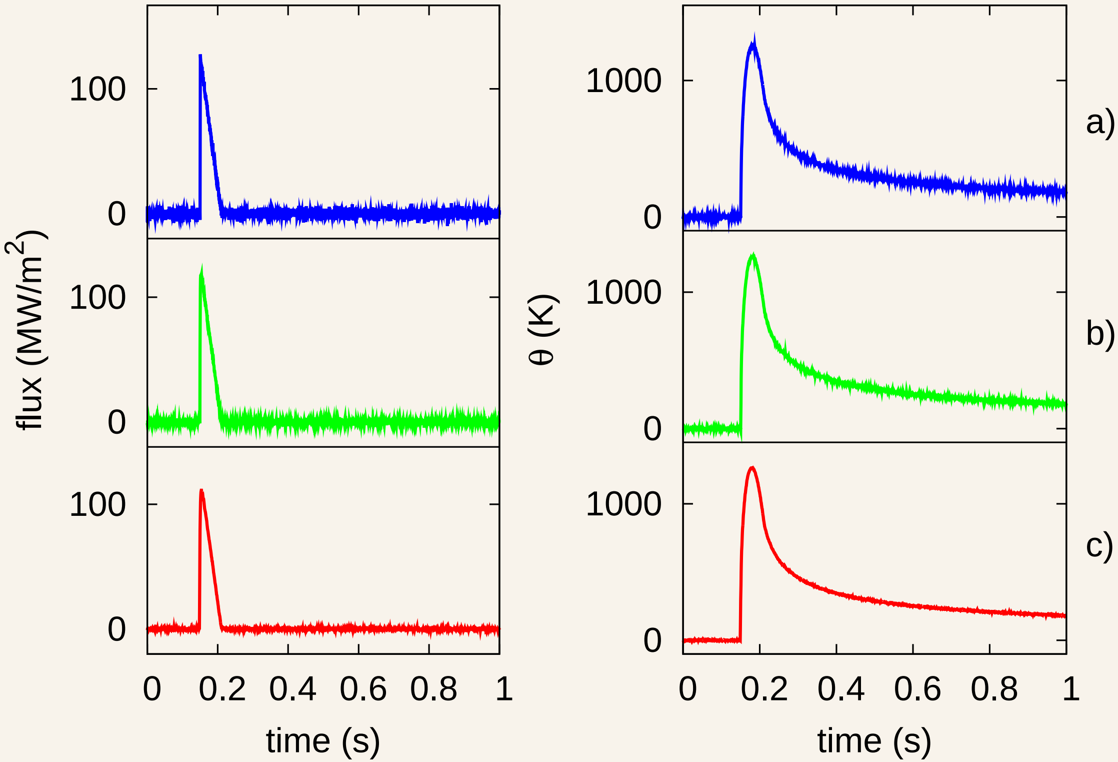
- Time of flight (TOF) was calculated from exact temperature solution
- Red: square flux; Green: triangle; Blue: reverse sawtooth





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

Test case estimates

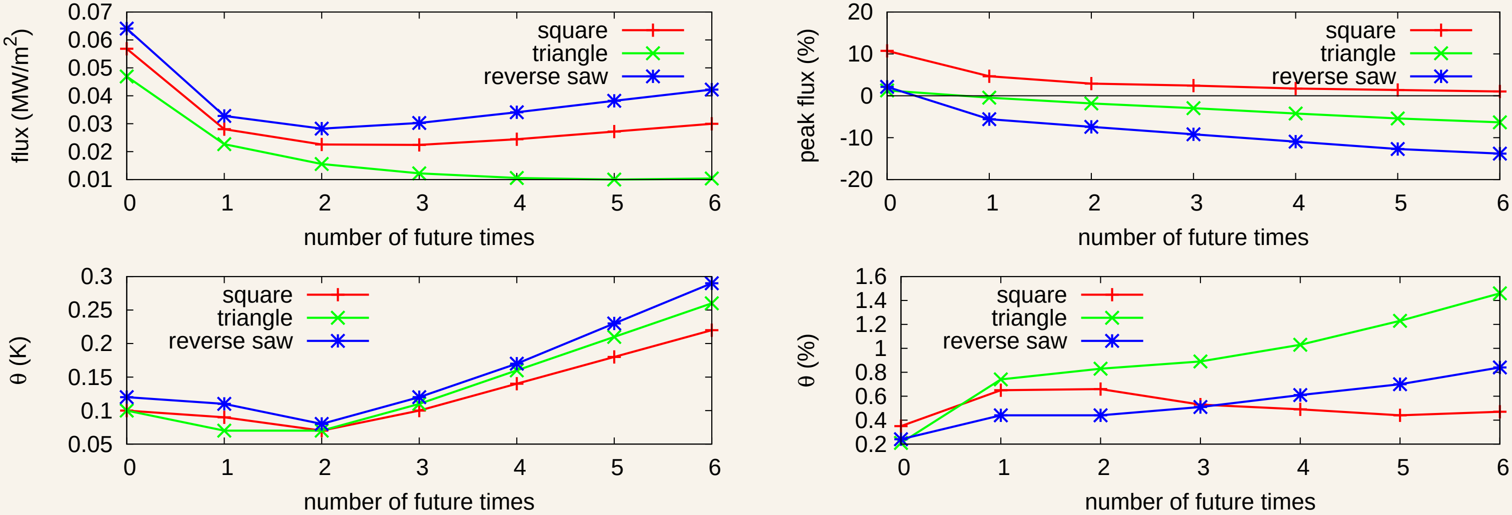


a) exact matching; b) 1 future time; c) 4 future times

Test case errors

RMS

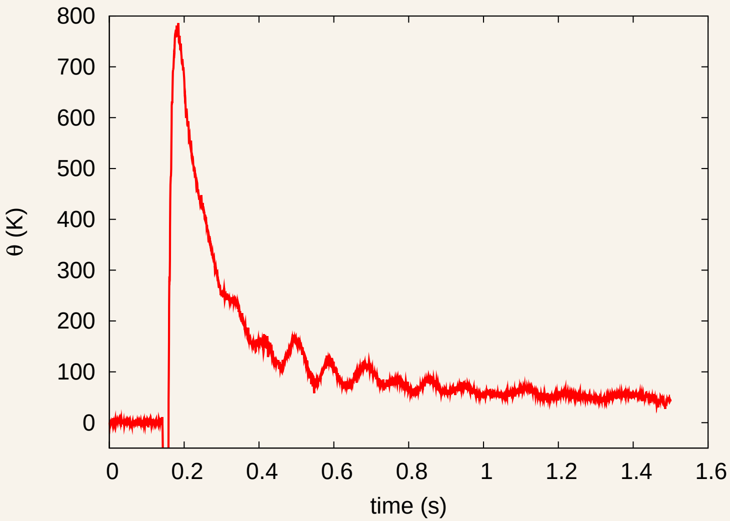
Peak



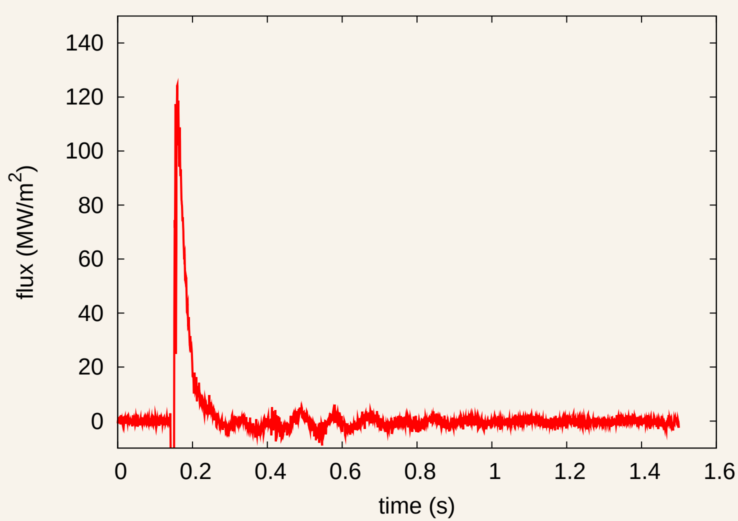
- **Observations**
  - reverse sawtooth has largest RMS errors and misses the peak flux
  - no future times (exact matching) captures peak best except for square flux
  - “best” RMS estimate provided with 2 future times

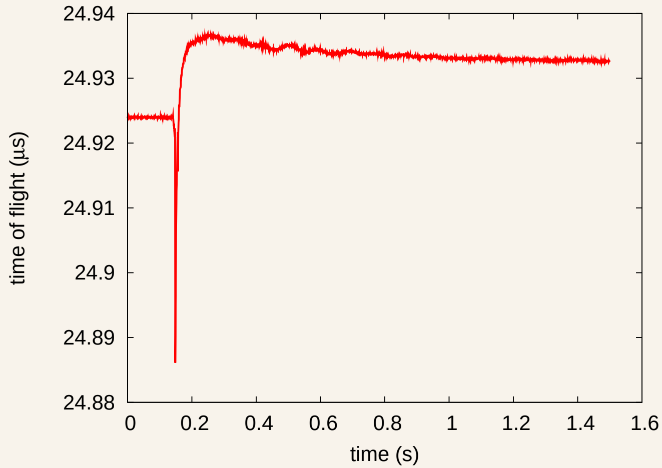
Gun test

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

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