Thruster Pulsing

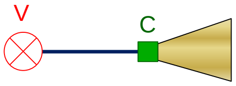
- So far all the analysis of rocket and thruster performance has assumed steady flow
- Most space thrusters (e.g., attitude control) are operated in pulsed mode
  - short burst of propellant
  - to get desired impulse, vary
    - pulse length
    - number of pulses of fixed length

$$I_{pulse} = \int_{pulse} \tau(t)\,dt$$

$$I = N_{pulses} \times I_{pulse}$$

- How to model pulsed operation?
- What limits minimum impulse “bit”?

Time Response - Limits



- Time response of thruster limited by various components
  1. valve response (open/close times) — *< 10 ms, low delay important for real-time control*
  2. feed line delay (valve to injector) — *depends on line length, diameter*
  3. ignition delays — *10+ ms cold catalyst*, *1-2 ms hot catalyst*
  4. pressure rise time (fill reactor and heat catalyst bed) — *depends on* $\dot{m}$*, chamber size,* A_t
  5. pressure fall time (similar)

Unsteady Pressure: Fall Time Example

- If nozzle stays choked

  and reaction chamber (rc) dominates volume upstream of throat

$$\dot{m}_t = f(\gamma)\frac{p_o(t)}{\sqrt{RT_o(t)}}A_t$$

$$m_{rc} = \rho_{rc}V_{rc} = \frac{p_o}{RT_o}V_{rc}$$

- From mass conservation $\frac{dm_{rc}}{dt} = -\dot{m}_t$

$$\frac{V_{rc}d\left(\frac{p_o(t)}{RT_o(t)}\right)}{dt} = f(\gamma)\frac{p_o(t)}{\sqrt{RT_o(t)}}A_t$$

- Assume reactions complete when valve closes and temperature in rc constant

$$\frac{d\left(p_o(t)/T_o(t)\right)}{p_o(t)/\sqrt{T_o(t)}} = f(\gamma)\frac{\sqrt{R}A_t}{V_{rc}}dt$$

$$\frac{dp_o}{p_o} = -f(\gamma)\frac{\sqrt{RT_o}A_t}{V_{rc}}dt$$

- Solution

$$p_o(t) = p_{o,\max}\exp\left(-f(\gamma)\frac{\sqrt{RT_o}A_t}{V_{rc}}t\right)$$

exponential decay

Typical Pulse Behavior

- Under proper conditions (long enough pulse duration), thrust can reach plateau at rated thrust
- If pulse duration >> rise+fall time

  $I_{bit} \cong \tau_{rated}\Delta t_{pulse}$

- What happens to specific impulse?

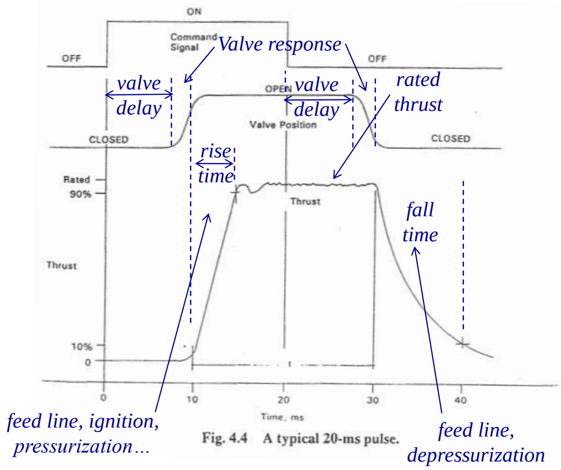
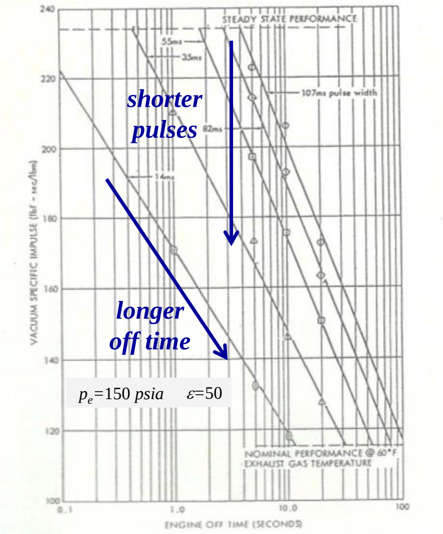


Fig. 4.4 A typical 20-ms pulse.

from C. Brown, ***Spacecraft Propulsion***, *AIAA Education Series (1996)*

Specific Impulse

- I_{sp} drops for
  - short pulses
  - thruster off for long time before pulse $\Rightarrow$ low duty cycle $\equiv \Delta t_{pulse} \big/ \Delta t_{between\ pulses}$
- Why?



shorter pulses

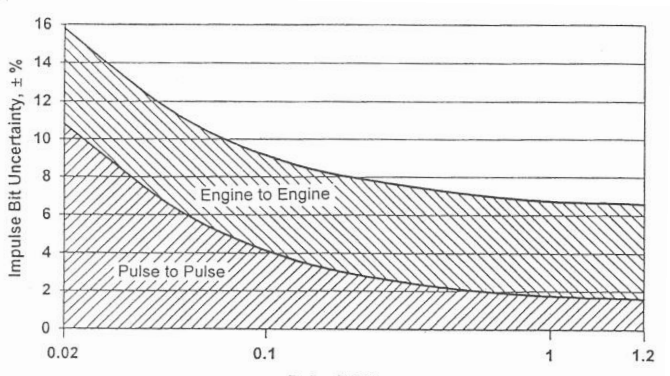
longer off time

p_e=150 *psia* ε=50

Fig. 4.5 Pulsing specific impulse of hydrazine (from Ref. 10, P. 65).

from Brown

Repeatability



from Brown

Fig. 4.6 Typical impulse bit variability for small engines.

- Why less variability with longer pulse widths?

lower fraction of pulse is rise/fall

Sizing and Cycling

- Thrust-to-weight for thruster roughly constant until thruster gets too small
  - – ancillary equipment limited (weight of valves, lines, heaters, …)
- Cycling
  - – what limits how many thruster starts can be achieved
    - for cold starts, large pressure pulses are created – lots of propellant in chamber before ignition occurs
    - pressure pulses can physically damage catalyst pellets
    - preheating catalyst bed reduces ignition delay and therefore pressure pulse ($T_{preheat}$ ~ 475-600 K with electric heater)
  - – can achieve 100,000’s of cycles
    - example: Voyager MR-103 >400,000 cycles (1977)