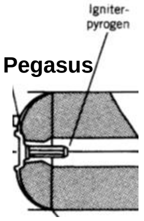
Solid Rocket Motors

Transients and
Combustion Instability

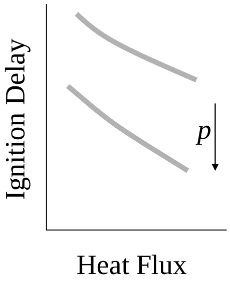
Solid Motor Unsteady Combustion

- Two parts of motor firing are by definition transient phenomena
  - ignition
  - extinction/termination
- Can have also have unsteady combustion during what should be nominally steady operation
  - combustion instability

Ignition



- Goal is obviously successful ignition
  - pyrotechnics/pyrogens most common
- Need sufficiently large heat source to get enough of the propellant to burn such that
  - heat losses to surrounding propellant does not extinguish flame
  - motor pressure continues to sustainable level
    - recall poor burning at low pressure
- Additional goal may be shorter ignition delay
  - requires even greater ignition energy



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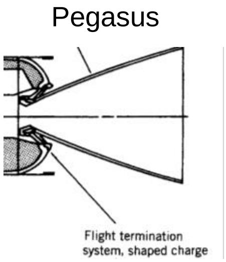
Extinction/Termination

- Motor will burn itself out when
  - no propellant left
  - amount of propellant (surface area) remaining is insufficient to keep pressure at sustainable level
- Motor can extinguish if sudden depressurization (dp/dt)
  - flame suddenly lifts farther from surface; remaining thermal energy in surface produces too much for flame to consume nearby and heat feedback too low
- Depressurization can be caused by
  - sudden increase in nozzle throat size
  - sudden "opening" of new exhaust path



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Combustion Instability

- Like liquid rockets
  - solid motors can experience unsteady operation due to feedback between motor conditions and propellant burning (dq/dt and dp/dt)
- Unlike liquid rockets
  - no separate propellant feed system
  - no spray/atomization
  - combustion feedback not localized to head end
    - combustion occurs along full length for port burning
  - chamber volume (and cross-section) not constant
  - chamber lined by acoustically dissipative, compressible material

excellent reference: *Nonsteady Burning and Combustion Instability of Solid Propellants*, Vol. 143, *Progress in Astro. and Aero.*, ed., De Luca, Price and Summerfield

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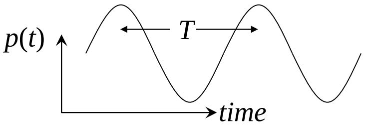
Types of Combustion Instability

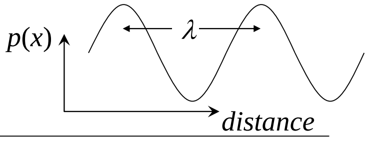
- Low frequency
  - “non-acoustic”
  - spatially uniform pressure oscillations
  - ~5-300 Hz
- Intermediate frequency
  - longitudinal acoustic modes of motor
  - ~15-1500 Hz
- High frequency
  - transverse acoustic modes of motor
  - ~1000-15,000 Hz

Characteristic Times



- Instability period
  - $T = 1/f$
- Residence (flushing) time of motor chamber
  - $t_{res} = m/\dot{m} = \rho_o V_o / \dot{m}$
- Relaxation time of propellant combustion wave
  - can be due to thermal wave in condensed phase of propellant (t_{th})
  - gas flame response (t_{fl})
- Also can describe wavelength (λ) of oscillation in motor

$\lambda = a / f$

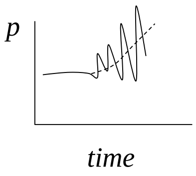


Low-Frequency Instability

- Spatially uniform pressure oscillations
  - essentially Helmoholtz resonator
- Attributable when $T/t_{res} > 1$
- Also called
  - chuffing/chugging
  - bulk mode
  - L^* (sometimes occurs when $L^*=V_o/A_t$ too low)
    - lowest L^* during initial portion of burn
- Primarily driven by response of propellant combustion to pressure oscillation
- Can be addressed analytically to reasonable degree
  - occurs for t_{res}/t_{th} ($\equiv Da$) ~ 0.2

High Frequency Instability

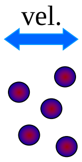
- Transverse modes
  - $\lambda \sim 2D$ ("characteristic" lateral dimension of internal volume) and harmonics
  - $f \sim a/2D$
  - D not constant ⇒ resonant frequency(s) evolve
- If oscillations grow, mean burning rate also increases
  - rapid rise in transient & mean pressure (and thus thrust)
  - can lead to catastrophic failures (many early motors)



- Thought to be driven primarily by response of propellant combustion to pressure oscillations (as opposed to "velocity-coupling")

High Frequency - Damping

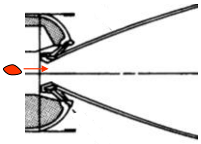
- Growth and maximum amplitude of oscillations controlled by feedback vs. damping
- Various damping sources
  - radiation out of nozzle (typically low level damping)
  - drag of condensed phase material in flow
    - e.g., Al_2O_3
    - depends on particle loading and size distribution (frequency dependence)
  - viscous/turbulent/vortical dissipation of acoustic energy



- **Control approaches**: particle size/loading (Al or inerts); port cross-section; rods and baffles

Intermediate Frequency Instability

- Longitudinal modes
  - $\lambda \sim L$
  - modes do not change much with time (but which modes have energy can)
- Can produce large increase in mean burning rate when oscillation is large
- Can be triggered by flow disturbances
  - slivers, vortex shedding, …
- Damping
  - low enough f that particle damping small
  - nozzle damping higher
- Main flow and acoustic wave co-linear
  - "velocity-coupling" more important than with transverse modes



Instability Modeling

- Analysis and characterization of instabilities for design purposes often broken into
  - (non-reacting) acoustic problem
  - combustion response function (assumes feedback based on near surface processes)
  - coupled by interface condition (acoustic admittance)
- Velocity coupling requires more sophisticated approaches
  - one example is jet/vortex shedding from slots between segments in large segmented motors

Measuring Combustion Response Function

- Measured for propellants in simplified burner
- One standard approach is the "T-burner"
  - – center vented, symmetric
  - – frequencies determined by (changing) length
  - – low Mach number near propellant to minimize mean flow velocity effects
  - – analytic model of T-burner used to determine combustion response function (f, T, p, …)