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LRE Combustion Instability

Some Basics

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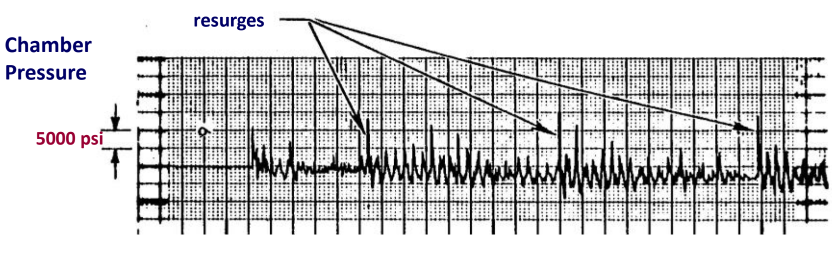
Combustion Instability in F-1 Engine

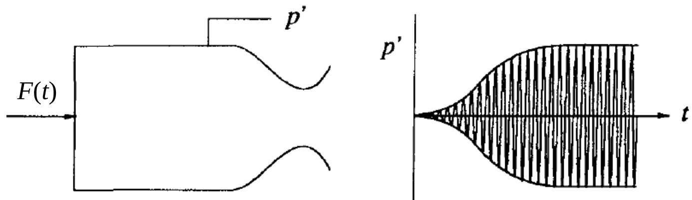
- Typical combustion instabilities observed in early F-1 engines



from V. Yang

Acoustic Pressure Oscillations

- Can approach them from point-of-view of dynamic system modeling



Limit Cycle

Resonant Frequency

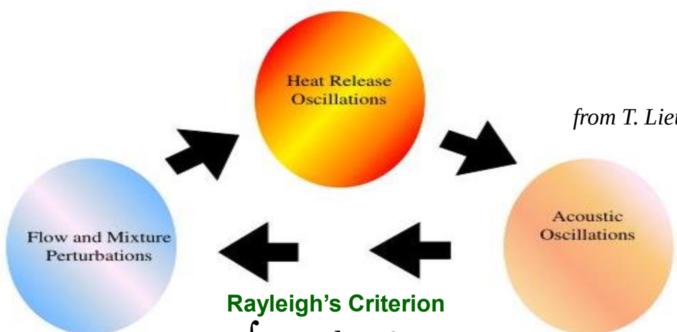
$$\frac{d^2 p'}{dt^2} + 2\alpha \frac{dp'}{dt} + \omega_o^2 p' = F(t)$$

Forcing Function

Gain/Damping

after Culick and Yang, Overview of Combustion Instabilities in Liquid Propellant Rocket Engines

Feedback Loops in Combustion Instability



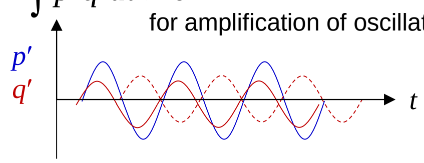
from T. Lieuwen

Rayleigh's Criterion

$$\oint p'q'\,dt > 0$$

for amplification of oscillations

- Gas that burns (heat release) expands, and generates compression waves



Combustion Driving

- Ways that heat release can be made to fluctuate and lock-in to pressure oscillations
  - bulk reactant flowrates respond to $\Delta p_{injection}$
    - can also impact atomization
    - interact with pump cavitation
  - acoustic pressure fluctuations correlate to acoustic velocity fluctuations
    - can impact flow within injectors and downstream of injectors
    - alters atomization, mixing, flame stabilization

Acoustic Resonances

- C.C. Longitudinal modes
  - $f \propto a/L$
- C.C. Transverse modes
  - radial and azimuthal/tangential
  - $f \propto a/R$
- Injector and manifold resonances

Frequency Based Nomenclature

- Chugging
  - low freq: f ~10-400 Hz
  - often related to propellant feed system oscillations
- Screeching (screaming)
  - high freq: $f > 1$ kHz
  - typically contains highest energy, most damaging
- Buzzing
  - intermediate frequencies

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Suppression

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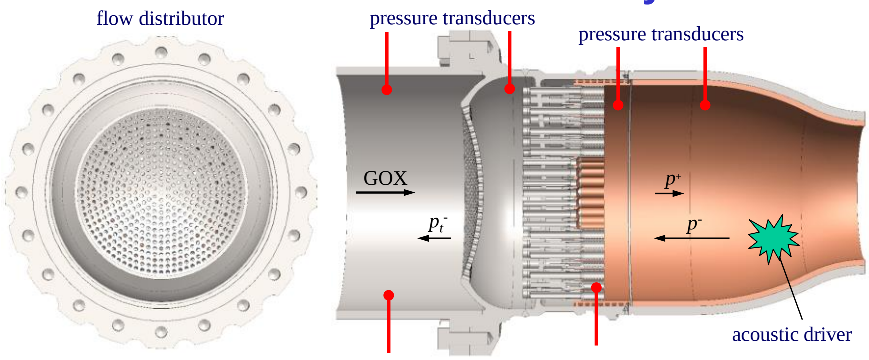
Main Combustion Chamber Dynamics



RD-170 Main Chamber Assembly

from V. Yang

$$\nabla^2 p' - \frac{1}{\bar{a}^2}\frac{\partial^2 p'}{\partial t^2} = h \equiv \text{linear} + \text{nonlinear sources}$$

$$\mathbf{n} \cdot \nabla p' = -f \quad \text{along boundaries}$$

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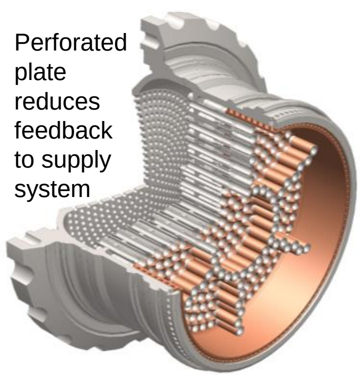
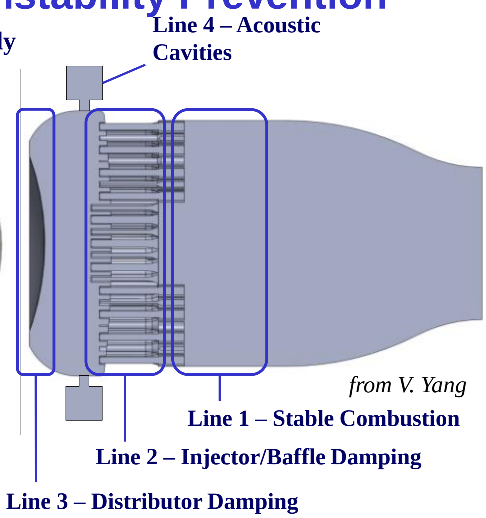
Combustion Instability Prevention

RD-170 Main Chamber Assembly

- Perforated plate reduces feedback to supply system



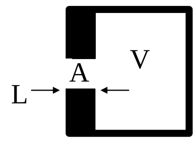


from V. Yang

- Baffles suppress transverse modes

Acoustic Cavities - Helmholtz Resonators

- Cavity acts to absorb pressure fluctuations from high p part of cycle and return it during low p
  - also produces jet leaving orifice that provides viscous damping
- Often placed
  - near injectors
    - important to suppress oscillations there
  - in corners
    - near pressure anti-node (spatial location with large p′)



$$f \cong \frac{1}{2\pi}\frac{a}{\sqrt{VL/A}}$$