COMSOL CONFERENCE
2018 BOSTON

University of CINCINNATI

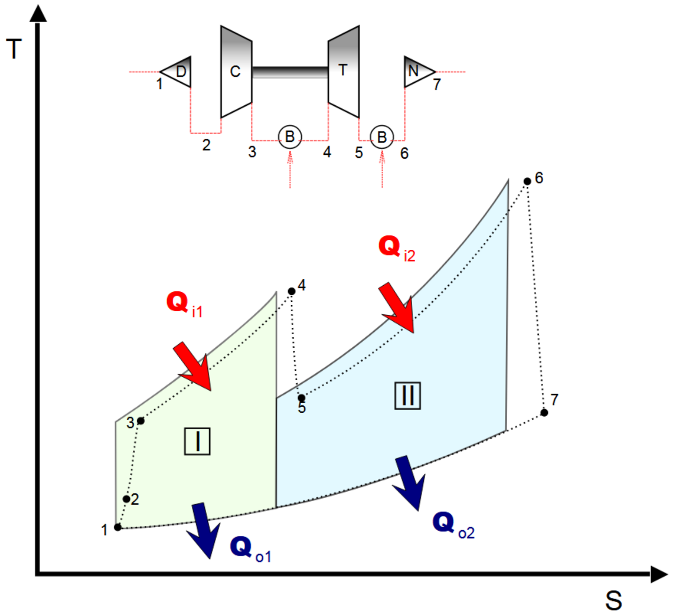
Augmentor Combustion Instability with COMSOL Multiphysics®

Vincent Shaw
Joshua Clabbers and Ephraim Gutmark
University of Cincinnati
Department of Aerospace Engineering & Engineering Mechanics
October 4, 2018

shawvt@mail.uc.edu

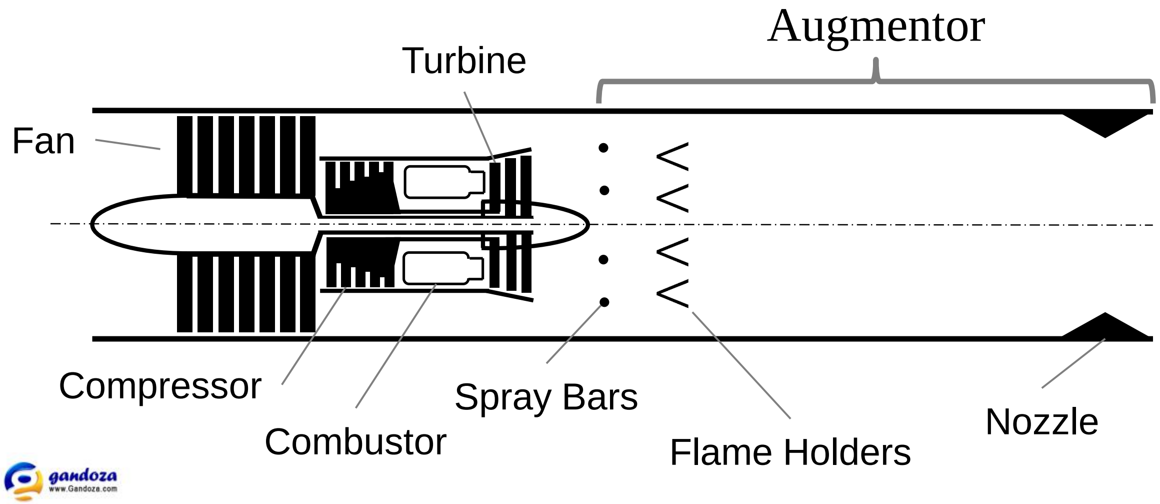
Jet Engine Thrust Augmentation

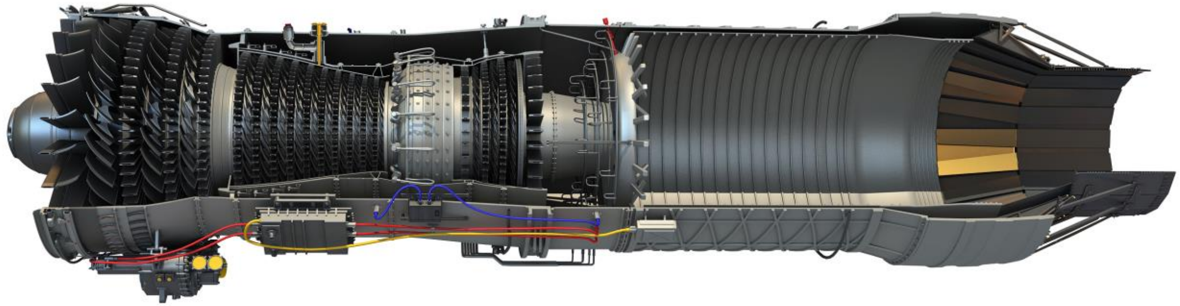
- Typical gas turbine cycles have good performance around a specific design point
- Certain applications require high thrust at a wide range of operating conditions
  - Military fighter aircraft and supersonic transport
- Maximum gas temperature is limited at the turbine inlet
  - Primary combustors operate lean, excess oxygen
- Remaining oxygen can be burned with additional fuel downstream of the turbine
  - Increased total temperature, increased exit velocity and thrust
- Augmented engine thrust levels equivalent to a larger engine without augmentation
  - Reduced specific fuel consumption, increased noise, and variable geometry nozzles



The Brayton Cycle with afterburning. [1]

Jet Engine Augmentors

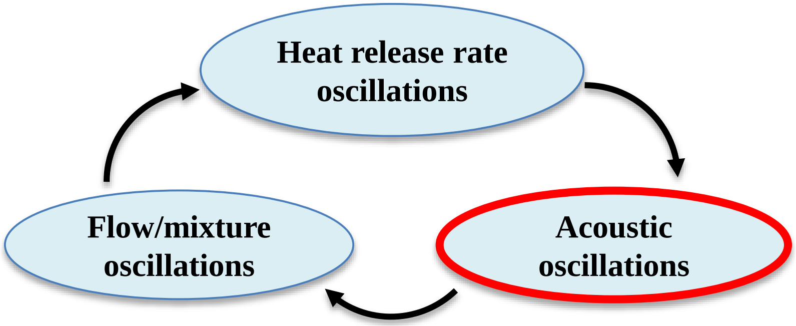




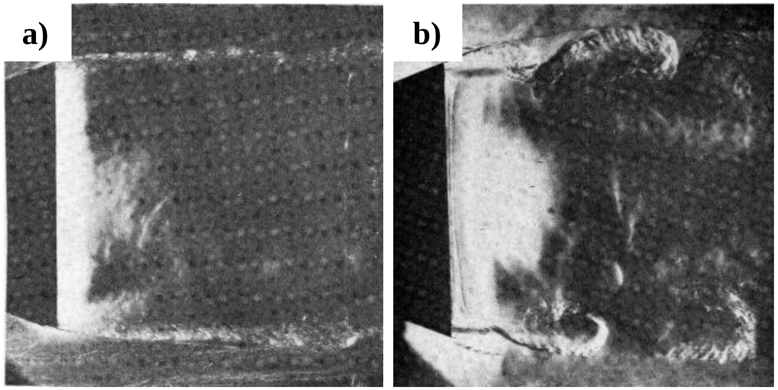
(U.S. Air Force photo by Senior Airman Matthew Bruch/Released)

Augmentor Combustion Instability

- Heat release rate oscillations couple with resonant chamber acoustics
  - Intensified heat release and pressure fluctuations
- High frequency transverse oscillations (screech) are the most problematic
  - Accelerated component wear and risk of engine failure
- Perforated liners are traditionally used to suppress screech
  - Increase damping at the chamber walls
- Modern augmentors are more prone to screech
  - Screech frequencies below the effective range of liners
- New suppression strategy is needed
  - Must understand the driving mechanisms of screech

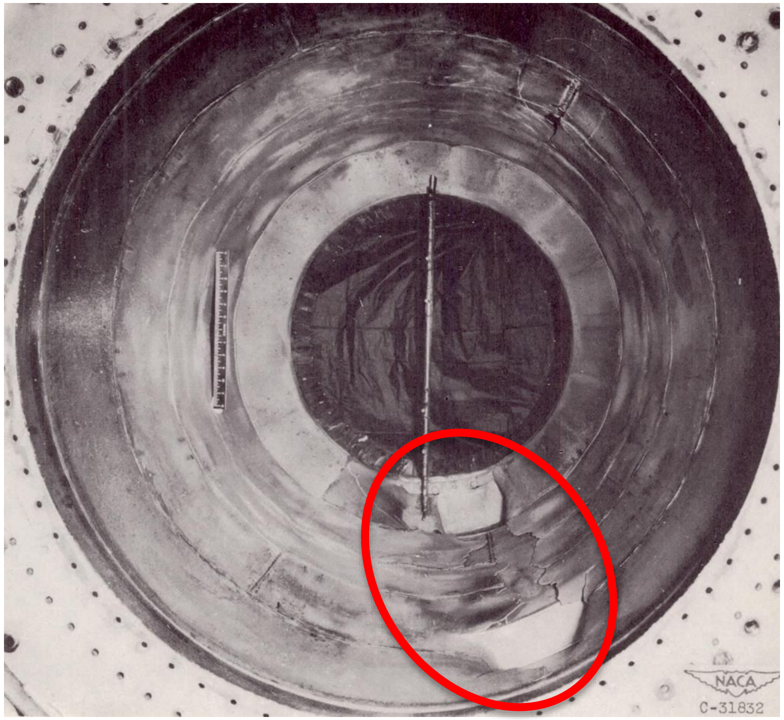


Thermoacoustic feedback cycle [2].

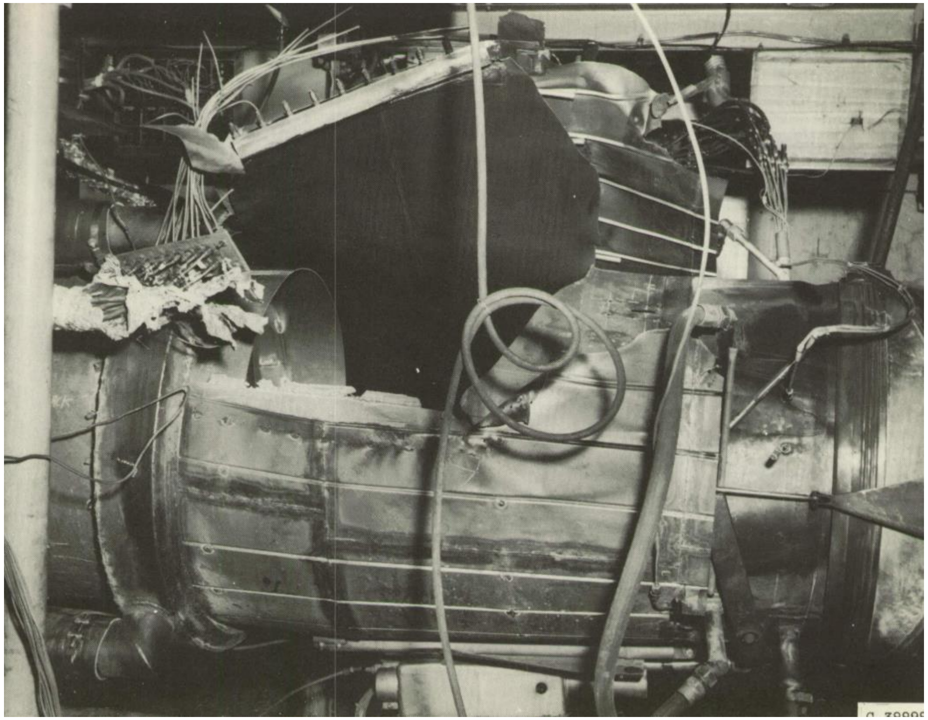


Schlieren photographs during a) smooth and b) screeching combustion [3].

Augmentor Screech Damage



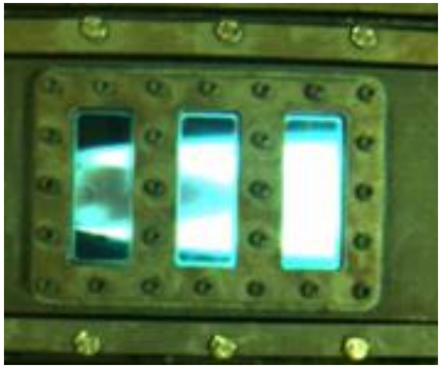
Destruction of augmentor shell due to screech [4].

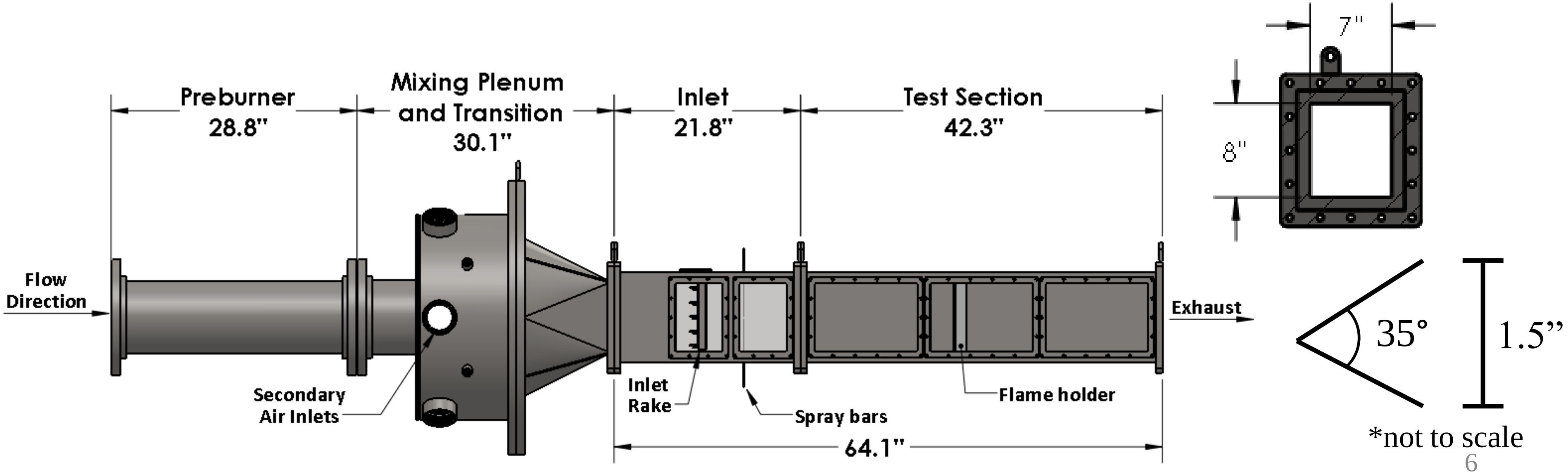


Augmentor shell rupture due to screech [5].

The UC Combustion Wind Tunnel Facility (CWTF)

- The CWTF replicates the inlet conditions of gas turbine augmentor
- Combustion instabilities observed from 100-2300 Hz
- Complete characterization of an instability requires extensive acoustic measurements





Motivation for COMSOL

- CWTF acoustic measurements via 12 pressure transducers
  - Partial acoustic field reconstruction
  - Infer mode frequency and shape from Eq. 1
- Eq. 1 applies to empty, closed-end, isothermal duct
- How well does Eq. 1 apply to the CWTF
  - Boundary conditions (open-open)
  - Complex internal geometry (flame holder)
  - Temperature gradient (flame)
- Additional physics easily added
  - Heat transfer, flow, chemical reactions
- Prediction of combustion instabilities

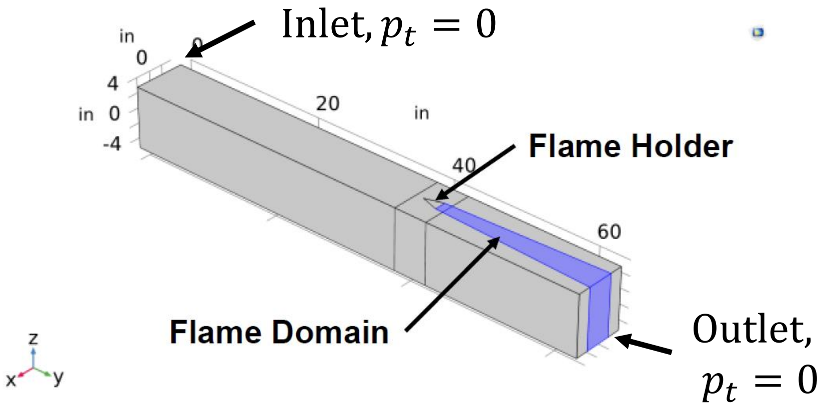
$$f_{l,m,n,} = \frac{c}{2}\sqrt{\left(\frac{l}{L}\right)^2 + \left(\frac{m}{H}\right)^2 + \left(\frac{n}{W}\right)^2} \qquad (1)$$

$$c = \sqrt{\gamma R T}$$

- $f_{l,m,n}$ – eigenfrequency
- c – is the speed of sound
  - γ – ratio of specific heats
  - R – gas constant
  - T – temperature
- $L, H,$ and W – length, height, and width of the duct, respectively
- $l, m,$ and n – integer mode number is respective dimension

Geometry and Mesh

- Rectangular cross-section duct (7” x 8”)
  - Length of 64.1” (test section + inlet)
- Empty duct and the addition of a flame holder to the domain
  - Triangular cross-section (1.5” wide, 35° angle)
  - Leading edge at $y = 40"$
- Flame domain downstream of the flame holder
  - Large temperature gradient in approximate shape of a typical flame
- Mesh refinement around flame holder and temperature gradient
  - Empty duct, 197,164 tetrahedral elements
  - Flame holder and domain added, 716,599 tetrahedral elements

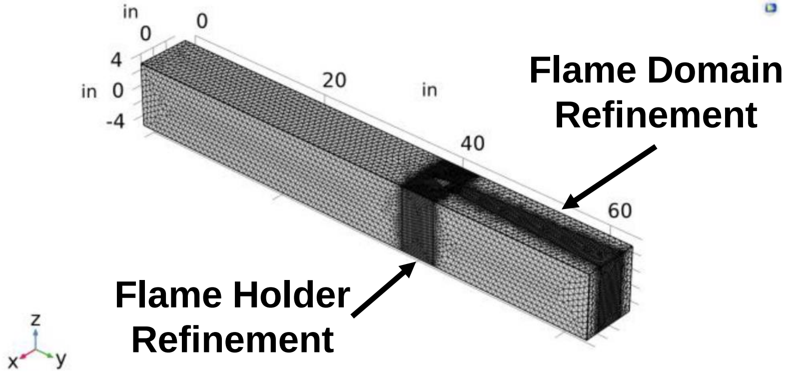


Inlet, $p_t = 0$

Flame Holder

Flame Domain

Outlet, $p_t = 0$



Flame Domain Refinement

Flame Holder Refinement

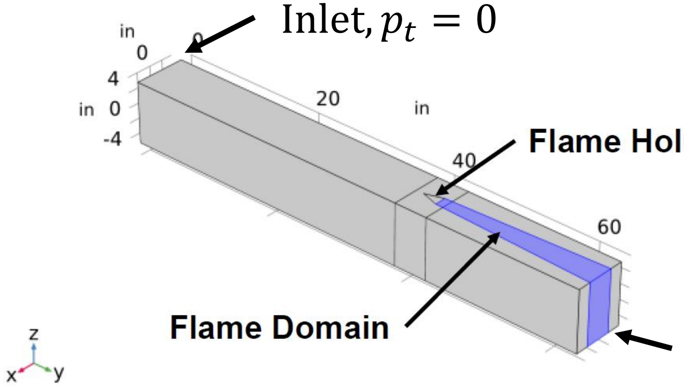
Governing Equations

- Pressure Acoustics, Frequency Domain (Eq. 2)
  - Solves Helmholtz Equation in the frequency domain
- Eigenfrequency Study
  - Eigenfrequency: resonant frequencies
  - Eigenmodes: normalized acoustic field
- Boundary conditions
  - Sound Soft ($p_t = 0$) – open-end
    - Inlet and outlet faces
  - Sound Hard (Eq. 3) – closed-end (wall)
- $T_{cold} = 293.15\ K, T_{Flame} = 1600K$

$$\nabla\cdot\left(-\frac{1}{\rho}(\nabla p_t - \boldsymbol{q}_d)\right) - \frac{k_{eq}^2 p_t}{\rho} = Q_m \qquad (2)$$

$$p_t = p + p_b, k_{eq}^2 = \left(\frac{\omega}{c}\right)^2, -i\omega = \lambda$$

$$-\mathbf{n}\cdot\left(-\frac{1}{\rho}(\nabla p_t - \boldsymbol{q}_d)\right) = 0 \qquad (3)$$



Inlet, $p_t = 0$

Flame Holder

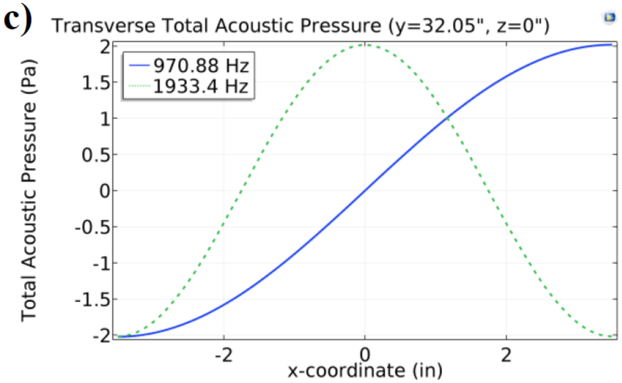
Flame Domain

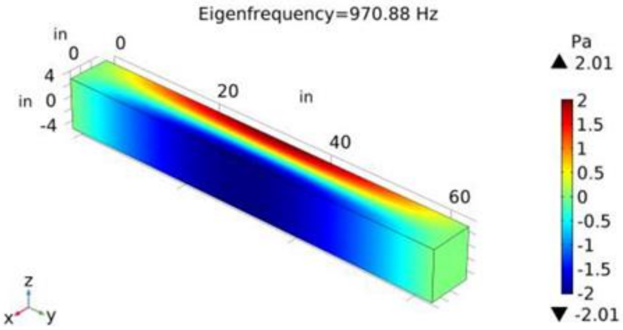
Outlet, $p_t = 0$

Baseline Case: Empty, Open-End Duct

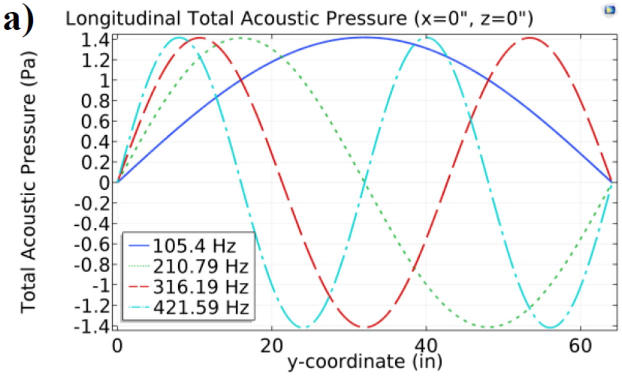
- Longitudinal modes have inlet and outlet pressure nodes
  - Mode number: number of pressure antinodes
  - Mode frequency matches Eq. 1
- Transverse modes have pressure antinodes at walls
  - Mode number: the number of pressure nodes
  - Mode frequency does not match Eq. 1
    - Longitudinal component to transverse modes

c)

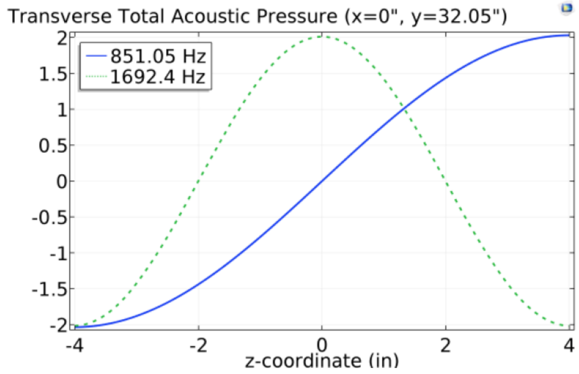




a)

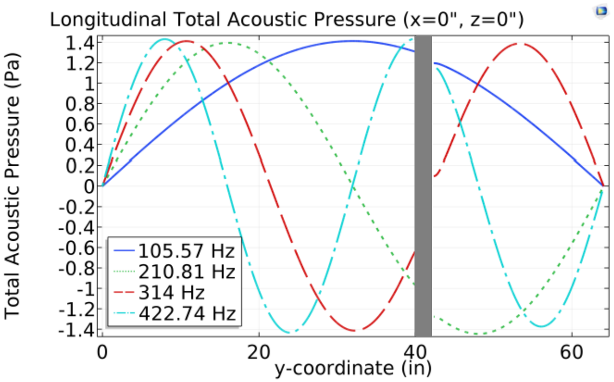


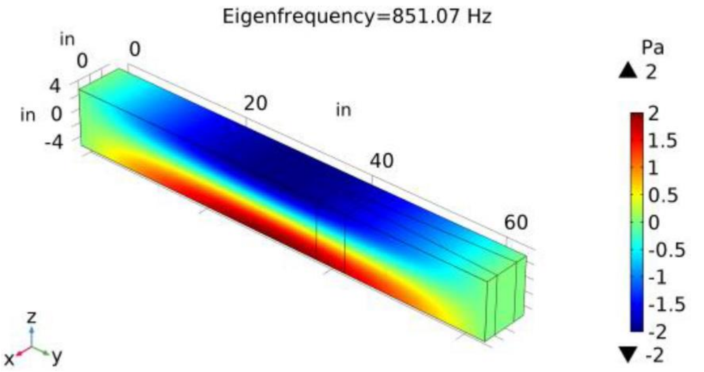
b)

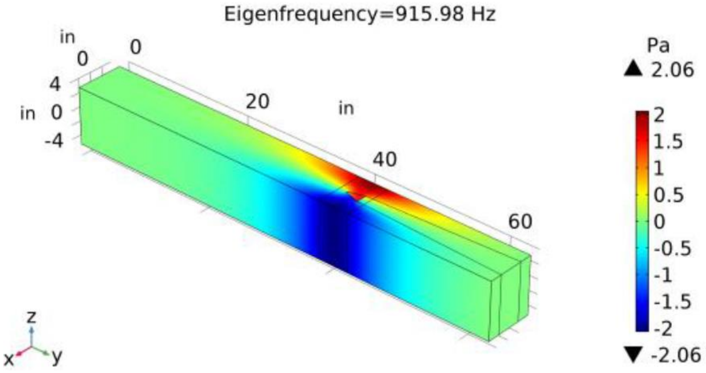


Open-End Duct with Flame Holder

- Minimal change in mode shapes and frequency for longitudinal modes
- No change for transverse modes along the length of the flame holder
- Transverse modes across the width of the flame holder change significantly
  - Mode concentrates around the flame holder and extends in a “V” shape upstream and downstream
  - Opposite oriented high pressure regions on the flame holder surfaces



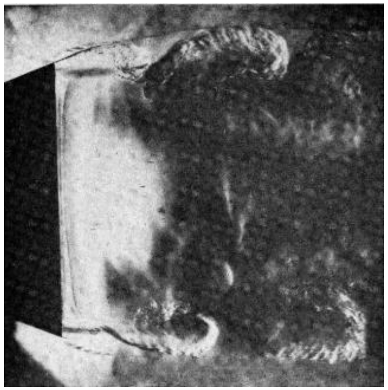




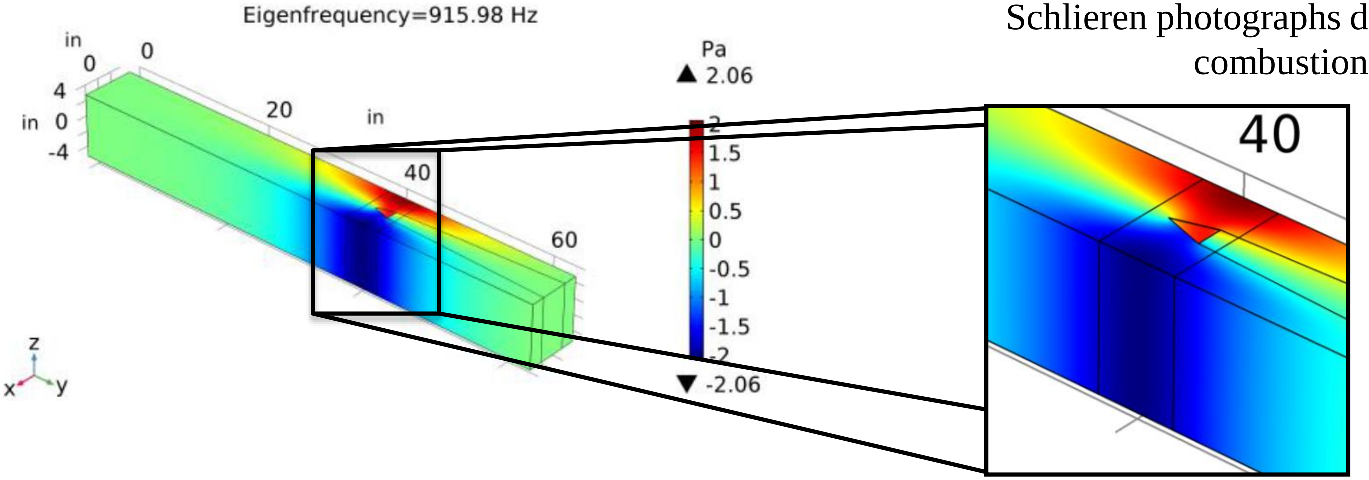
Open-End Duct with Flame Holder

Transverse Instability Implications

- 180° out-of-phase high pressure regions on the flame holder surfaces
  - Force the boundary layer such that vortices are shed in an alternating fashion
- Periodic transport of fresh reactants into the wake of the flame holder
  - Leads to oscillating heat release

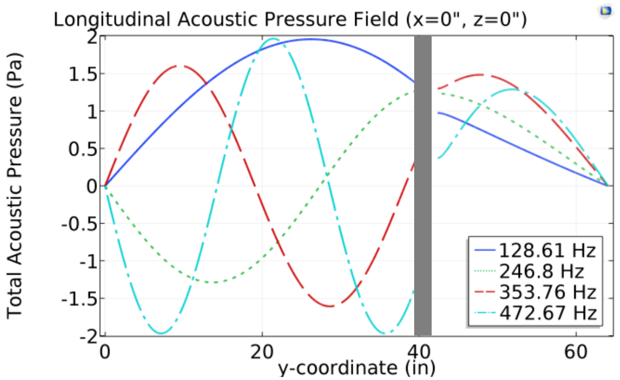


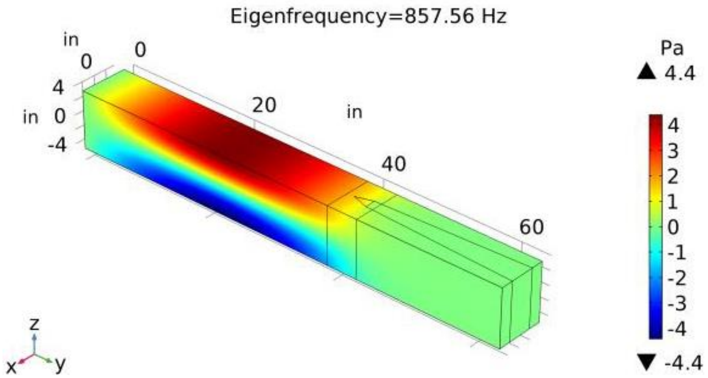
Schlieren photographs during screeching combustion [3].

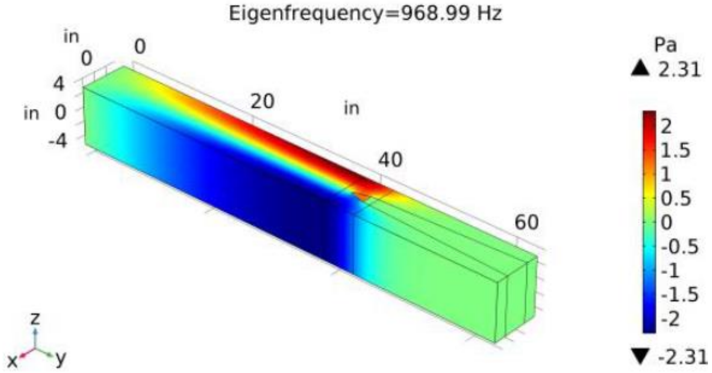


Open-End Duct with Flame Holder and Temperature Gradient

- $T_{Flame} = 1600K$
- Mode frequencies increases due to region of high temperature
- Transverse modes become concentrated to upstream domain
  - Reduced mode presence downstream of flame holder
  - 180° out-of-phase pressure regions still form on flame holder

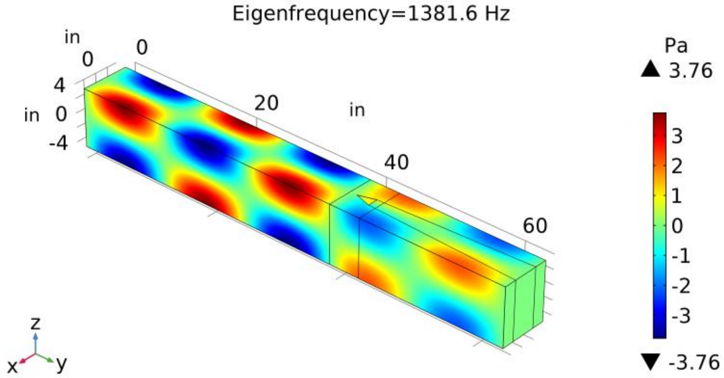




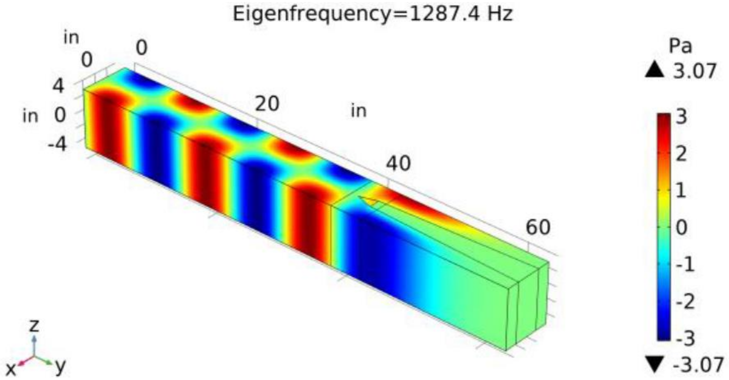


Combined Modes and Mode Transition

- Many more complicated cases exist
- Simultaneous modes
- Combined modes
  - Standing waves in multiple dimensions of the duct
- Mode Transition
  - Upstream longitudinal modes transition to transverse behavior downstream of the flame holder
- Numerous up and downstream pressure measurements for experimental detection
  - COMSOL simulation supplement and guide experiment



Combined Mode



Mode Transition

Conclusions and Future Work

- The addition of a flame holder to the domain significantly effects lateral transverse mode shapes
  - 180° out-of-phase high pressure regions on the flame holder surface suggests screech coupling mechanism
- Heat release concentrates transverse modes upstream of the flame holder
- COMSOL Simulation is a valuable tool for aiding the characterization of combustion instability

- Examine geometric changes to flame holder and flame domain
- Alter boundary conditions
- Add heat transfer, flow, and chemical reaction physics
- Continue to develop user-friendly GUI

shawvt@mail.uc.edu

References

1. https://commons.wikimedia.org/wiki/File:Brayton_Cycle_TS_Afterburner.svg
2. O'Connor, J., Acharya, V., and Lieuwen, T., "Transverse combustion instabilities: Acoustic, fluid mechanic, and flame processes," *Progress in Energy and Combustion Science*, vol. 49, 2015, pp. 1–39.
3. Barker, C. L., "Experiments concerning the occurrence and mechanism of high-frequency combustion instability," California Institute of Technology, 1958.
4. Usow, K. H., Meyer, C. L., and Schulze, F. W., "Experimental Investigation of Screeching Combustion in Full-Scale Afterburner," *NACA Research Memorandum*, vol. RM E53I01, 1953.
5. Lundin, B. T., Gabriel, D. S., and Fleming, W. A., *Effect of Operating Conditions and Design on Afterburner Performance*, Langly Field: 1956.

Instability Characterization

- Heat Release
  - High speed imaging (chemiluminescence)
- Flow
  - Particle Image Velocimetry (PIV)
- Acoustics
  - Water-cooled pressure transducer
  - **Modal Analysis:** 12 un-cooled Kulite piezoresistive transducers