Combustion Dynamics Course

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AE 6410  Combustion Dynamics

Catalog Description:
AE 6410: Combustion Dynamics. Credit (3-0-3). Analysis of acoustic wave propagation in inhomogeneous flows, flame-acoustic wave interactions, and control of combustion instabilities

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Meetings: By appointment

Textbook:
No text

References:
Course Notes and Handouts; recommended reading

Course Objectives:
Cover material/topics needed for understanding of combustion instabilities. This will require understandings the following three areas:
1) Linear and nonlinear stability concepts.
2) Wave propagation phenomenon in inhomogeneous environments; e.g., ducts with variable area and/or mean temperature and effect of boundary conditions.
3) Unsteady flame-acoustic wave interactions; e.g., combustion noise and self-excited, combustion driven oscillations.
4) Diagnostics of combustion instabilities; e.g., pressure and heat release rate measurements, data analysis.

Pre-requisites:
Graduate level background/knowledge of combustion.
Exams & Homework:

- **Midterm**: Closed book, closed notes
- **Final Project**: A final project will be assigned in place of an exam. This project will consist of a 10-15 page (double spaced) report on a specific combustion instability problem. It could be a review of a paper or a collection of papers on a specific combustion instability problem (e.g., driving of combustion instabilities in gas turbines) or an independent analysis of a specific combustion instability problem. Discuss your topic with the instructor before pursuing it.
- **Honor Code**: Students in this course and all other courses at Georgia Tech must abide by the Georgia Tech Honor Code. Please read the text of the Georgia Tech Honor Code which can be found on the internet at http://www.honor.gatech.edu/
Course Outline

I. Introduction

II. Historical Overview

III. Linear and nonlinear stability concepts

IV. Unsteady Flow Fields

V. Linear Acoustic Wave Propagation

VI. Thermo-acoustics/Stability analysis

VII. Nonlinear Analysis

VIII. Passive and Active Control of Combustion Instabilities

IX. Data Analysis and Experimental Methods
Needed Background/Understanding – Some of Which Will be Hopefully Acquired in This Course

- Combustion
- Acoustics
- Combustion Dynamics
- Design
- Modeling/theoretical
- Experimental
- Field work

- Combustion instabilities
  - Rayleigh’s criterion
  - Limit cycle
  - n-τ model of combustion response

- Acoustics
  - Plane waves
  - Resonance
  - Natural modes

- Mathematical tools
  - Complex notation
  - Fourier Transform
Reference List

- **General Acoustics:**
  - *Acoustics: An Introduction to its Physical Principles and Applications*, Pierce
  - *Theoretical Acoustics*, Morse and Ingard
  - *Acoustics of Ducts and Mufflers*, Munjal
  - *Thermoacoustics – A Unifying Perspective of Some Engines and Refrigerators* by G. W. Swift

- **Basic Combustion Fundamentals**
  - *An Introduction to Combustion*, Turns
  - *Combustion*, Glassman

- **Combustion Instabilities: Books**
  - *Theory of Combustion Instability in Liquid Propellant Rocket Motors*, Crocco and Cheng
  - *Combustion Instability*, Natanzon and Culick
  - *Combustion Driven Oscillations in Industry*, Putnam
  - *Liquid Propellant Rocket Combustion Instability*, Ed. Harrje and Reardon (NASA rpt.)

- **Combustion Instabilities: Papers**
Combustion-Driven Oscillations in Industry
Abbott A. Putnam

Elsevier
New York - London - Amsterdam
PULSATING COMBUSTION
The Collected Works of
F. H. Reynst

Edited by
Professor of Fuel Technology
and Chemical Engineering
University of Sheffield

PERGAMON PRESS
NEW YORK • OXFORD • LONDON • PARIS
1961
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What Causes Combustion Instabilities?

System

Fuel → Combustion Oscillations → Combustion products
Air

Acoustic Mode Oscillations

Driving

Acoustic Mode Oscillations are driven when:

\[ \tau_{\text{combustion}} \sim \tau_{\text{acoustic}} \]

\[ Q' \text{ occurs where } P' \neq 0 \]

\[ Q' \text{ and } P' \text{ have same frequency} \]

\[ \Phi - \text{phase between heat addition and pressure oscillations} \]

\[ Q' \parallel P' \]

Acoustic Oscillations are Driven when:

\[ |\Phi| < 90^0 \]

i.e., Rayleigh’s Criterion is satisfied

Damping

Acoustic Oscillations are damped by, e.g., viscosity, heat transfer, nozzle damping…

Stability

Instability Occurs When:

Driving of Oscillations > Damping of Oscillations
Combustion Instabilities

**Description:** A combustion instability occurs when one or more acoustic modes of the system are excited. This, in turn, results in periodic oscillations of the various system properties and processes (e.g., reaction rate, heat transfer rate, pressure, velocity).

**Examples:** Rocket motors; jet engines; ramjets; power stations, heaters and gas turbines
Figure 6. Illustration of a feedback processes that could drive combustion instability.
Figure 2. Examples of longitudinal and transverse acoustic modes that have been excited in cylindrical combustors.
Detrimental Effects of Combustion Instabilities

1. Increased heat transfer rates from the flow to the walls resulting in wall damage (e.g., melting),

2. Increased mechanical loading upon system components often results in increased mechanical stresses and, sometimes, components failures; it also results in premature wear of system components.

3. Introduction of undesirable vibrations in various system components, system instrumentation and system controls; vibrations which often result in mechanical failure and/or malfunction of the vibrating component.

Each or a combination of the above effects can result in system failure.
Combustion Instabilities

Transition to Limit Cycle Oscillations in a “Linearly” Unstable Combustor

![Graph showing the transition from stable operation to limit cycle oscillations over the number of cycles, with normalized pressure (p'/p) on the y-axis and number of cycles on the x-axis.]

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Combustion Instabilities

• Spontaneous combustion instability is initiated by a “linear mechanism” that produces an exponential growth of the amplitude of a small disturbance.

• A “limit cycle” is reached when the time average over a cycle of the energy added to the oscillations by the combustion process equals the time average of the energy lost by the oscillations due to, e.g., viscous dissipation, heat transfer and acoustic radiation.

• A linearly stable system can be destabilized by a finite amplitude disturbance.
Video from Ecole Centrale – 75 Hz
Video from Ecole Centrale – 50 Hz