Review of Active Control and Measurements of the Response of a Simple Flame

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Thank you:

Dr. Saadat Syed (Pratt & Whitney)

William Chen (Caltech)

I. Introduction and Incomplete History

II. The Earliest Results

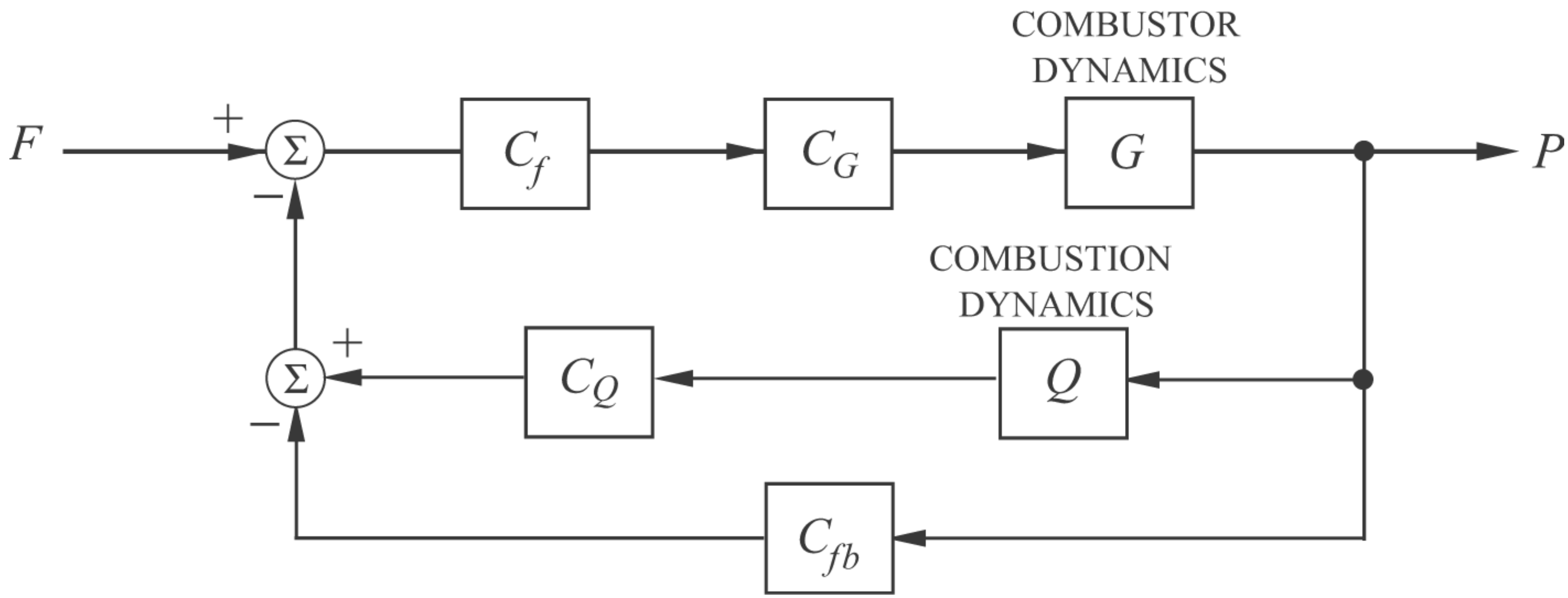
III. The First Practical Use of Active Control, 1995-2005

IV. Active Control of Large Gas Turbines for Flight

V. Measuring the Combustion Dynamics of a Simple Flame

VI. Concluding Remarks

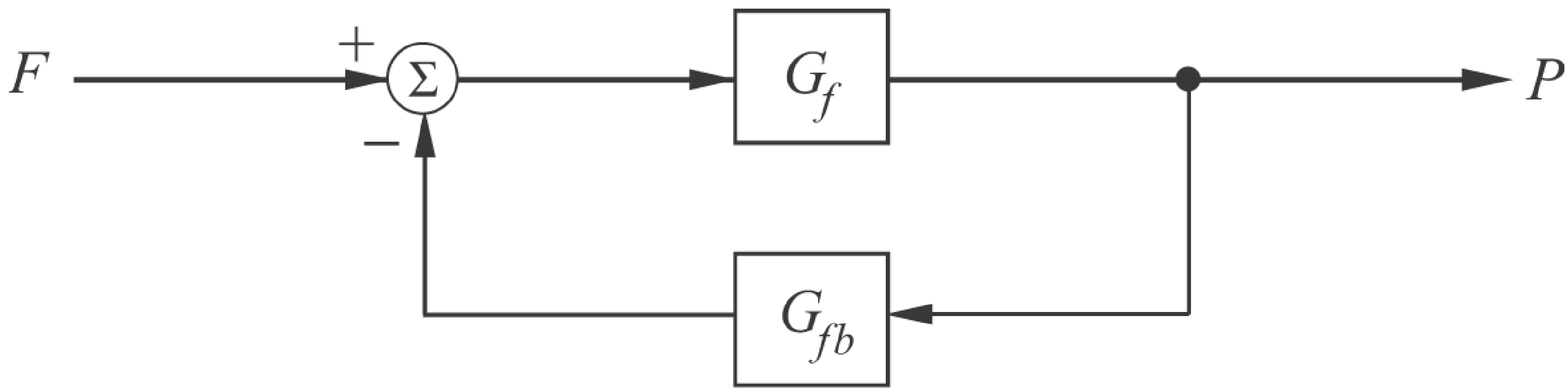
A System with Both Passive and Active Feedback Control



C_G, C_Q Passive Control

C_f, C_{fb} Feedback Control

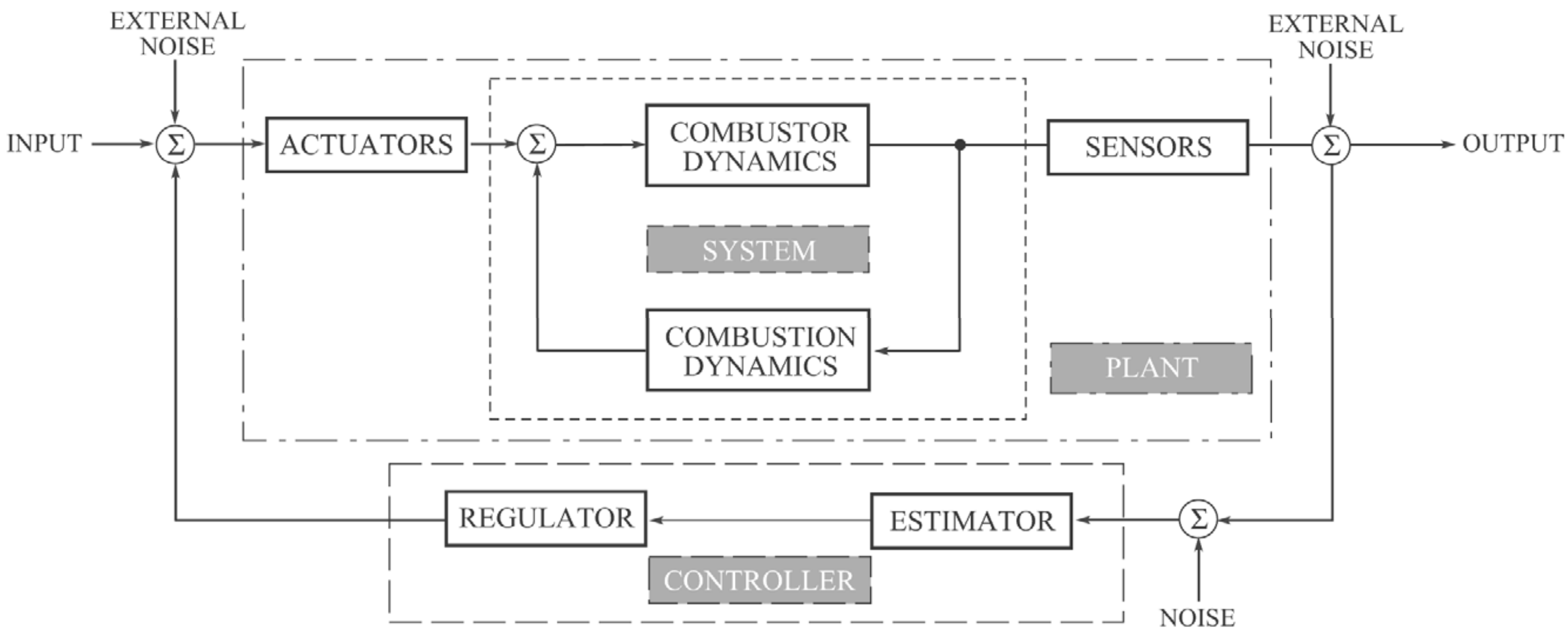
General Block Diagram



Distinguishing Features of Controlling Combustors

- Internal instabilities
- Substantial time lags
- Intrinsic nonlinearities
- Substantial internal noise
- The action of control changes the properties of the system

General Block Diagram, Classical and Modern Control



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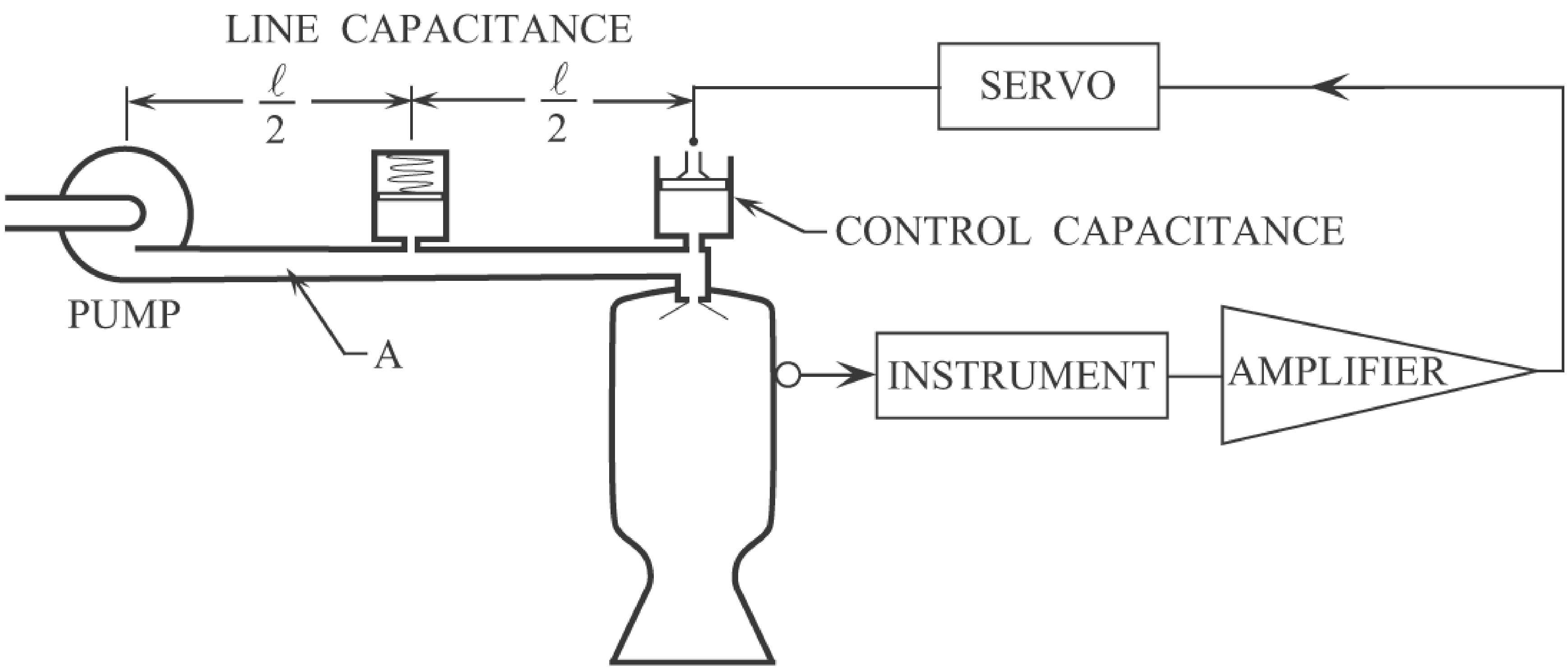
The First Proposal for Feedback Control of a Combustor (BOLLAY, 1951; TSIEN, 1952)

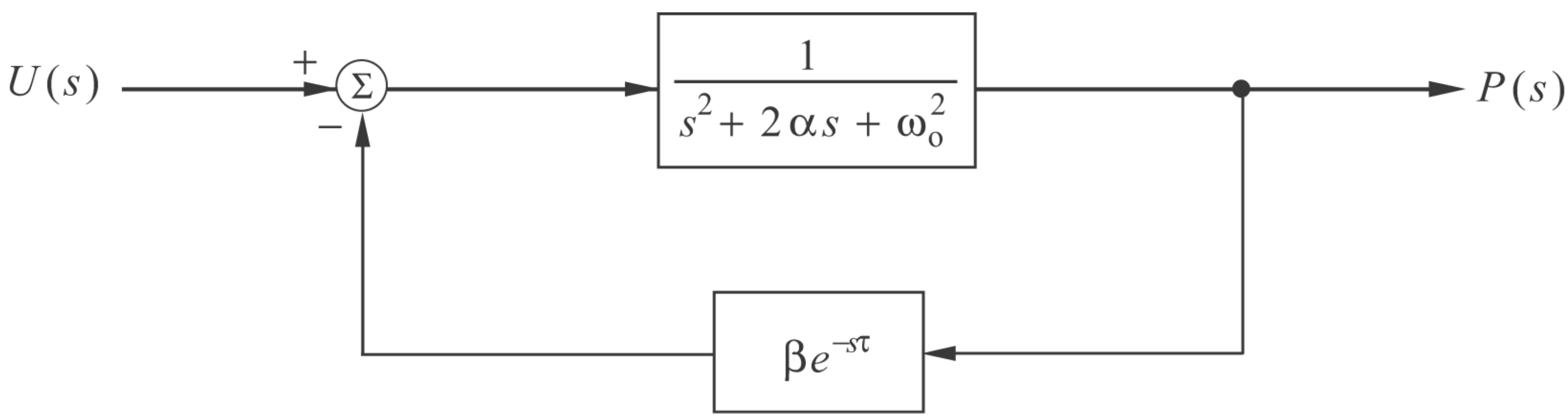


Tsien's Analysis

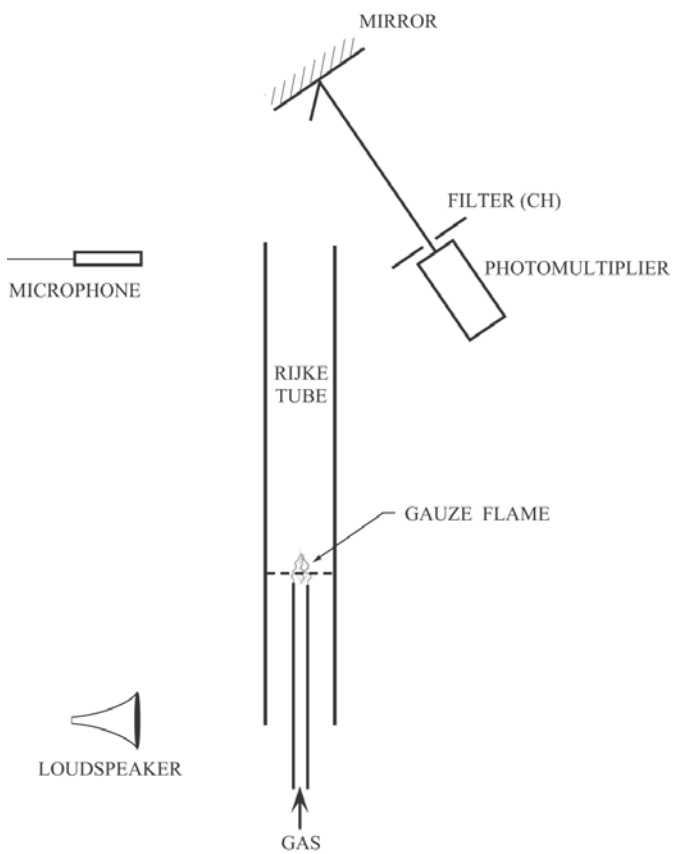
$$\frac{d^2 p'}{dt^2} + 2\alpha \frac{dp'}{dt} + \omega_0^2 p' = \beta p'(t - \tau) + u(t)$$

$$P(s) = \frac{\beta e^{-s\tau} G(s)}{1 - \beta e^{-s\tau} G(s)} U(s)$$

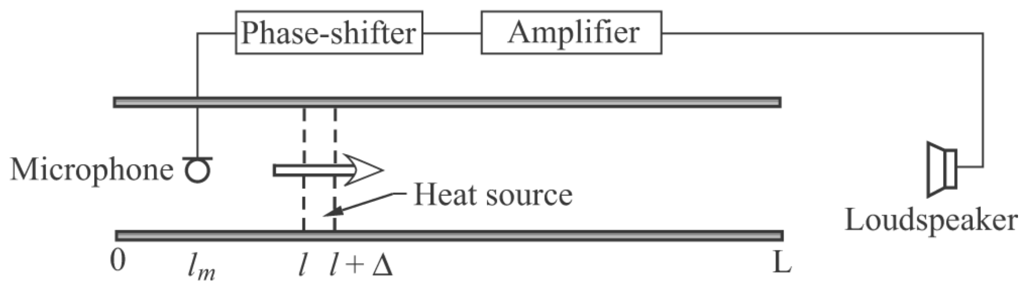
$$G(s) = \frac{1}{s^2 + 2\alpha s + \omega_0^2}$$



The First Cambridge Experiments

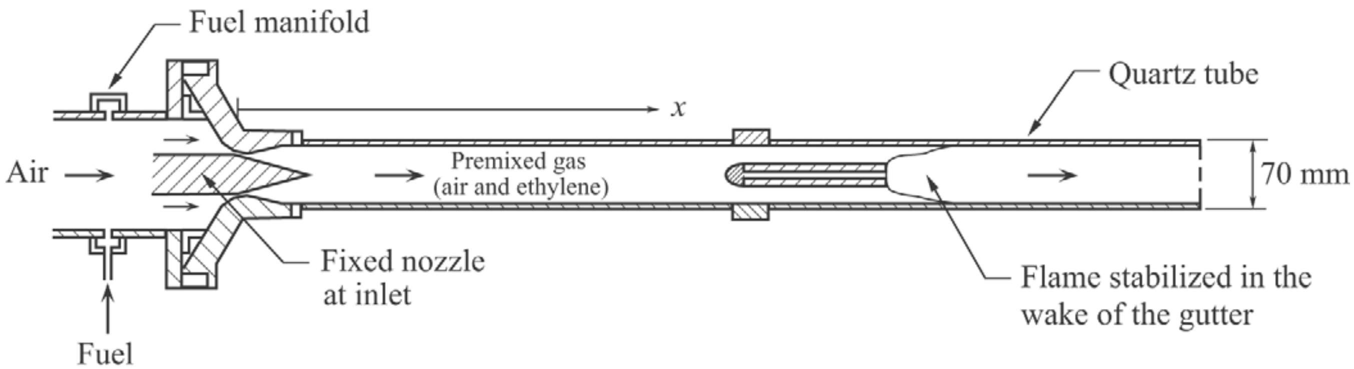


DINES 1983

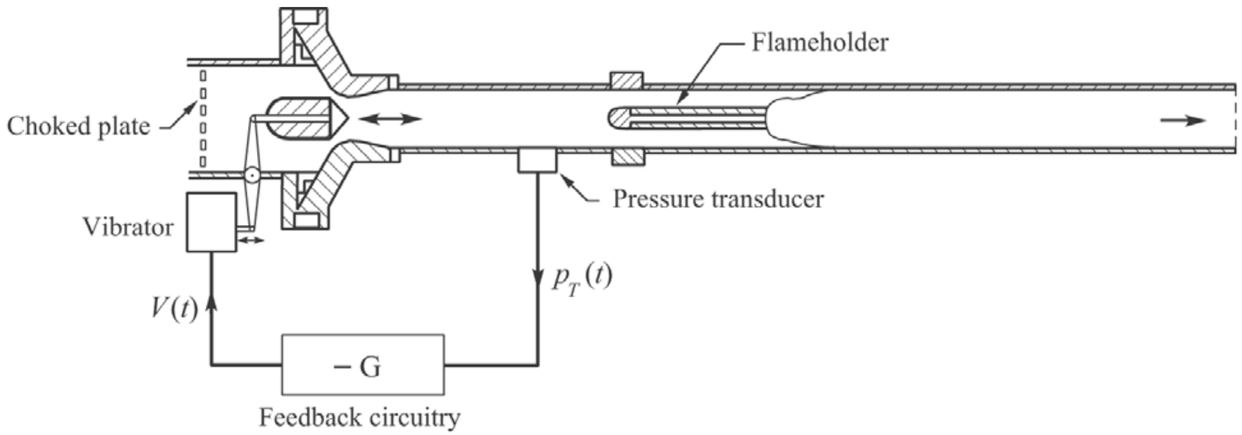


HECKL 1985, 1986

Cambridge Apparatus Modeling an Afterburner

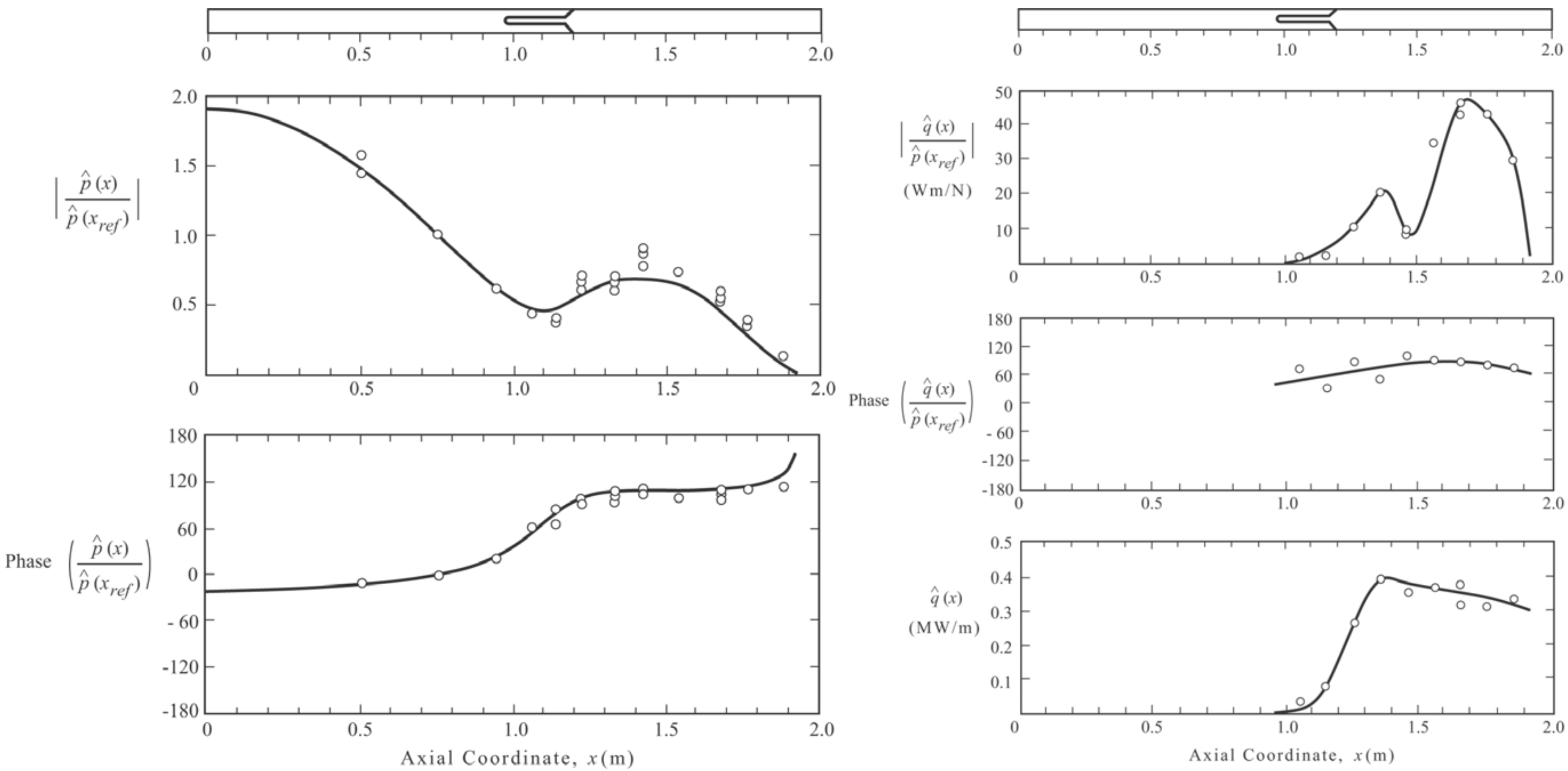


LANGHORNE 1988



BLOXSIDGE et al. 1988

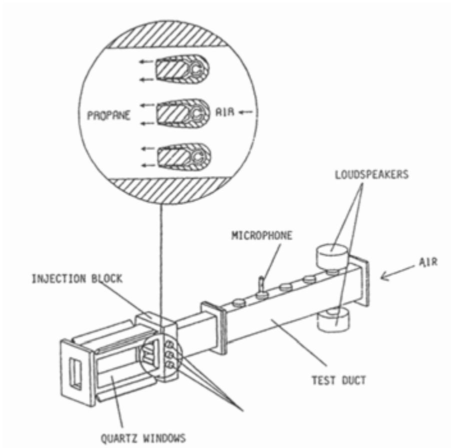
Cambridge Results

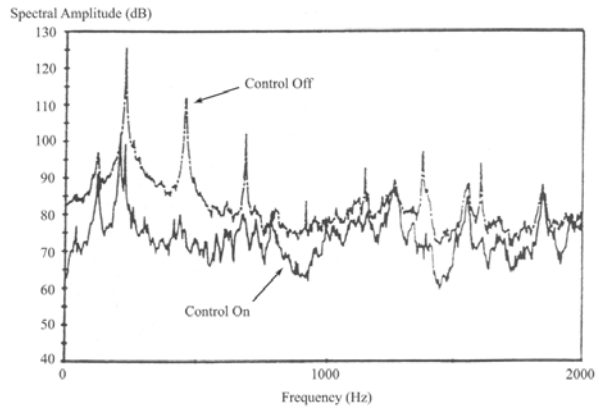


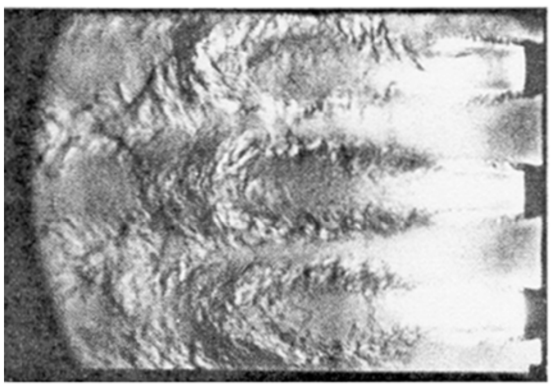
BLOXSIDGE et al. 1988

Feedback Control at École Centrale

POINSOT et al. 1987, 1988, 1989



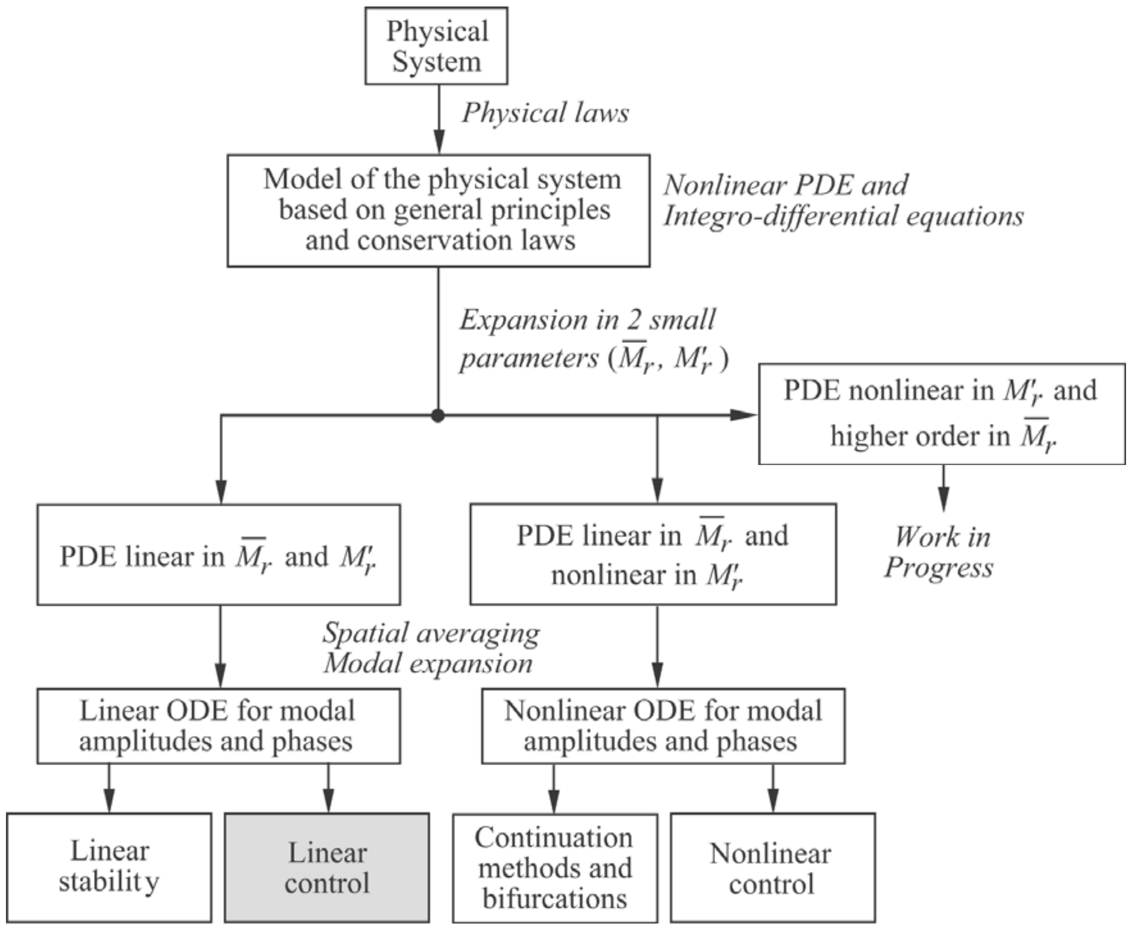




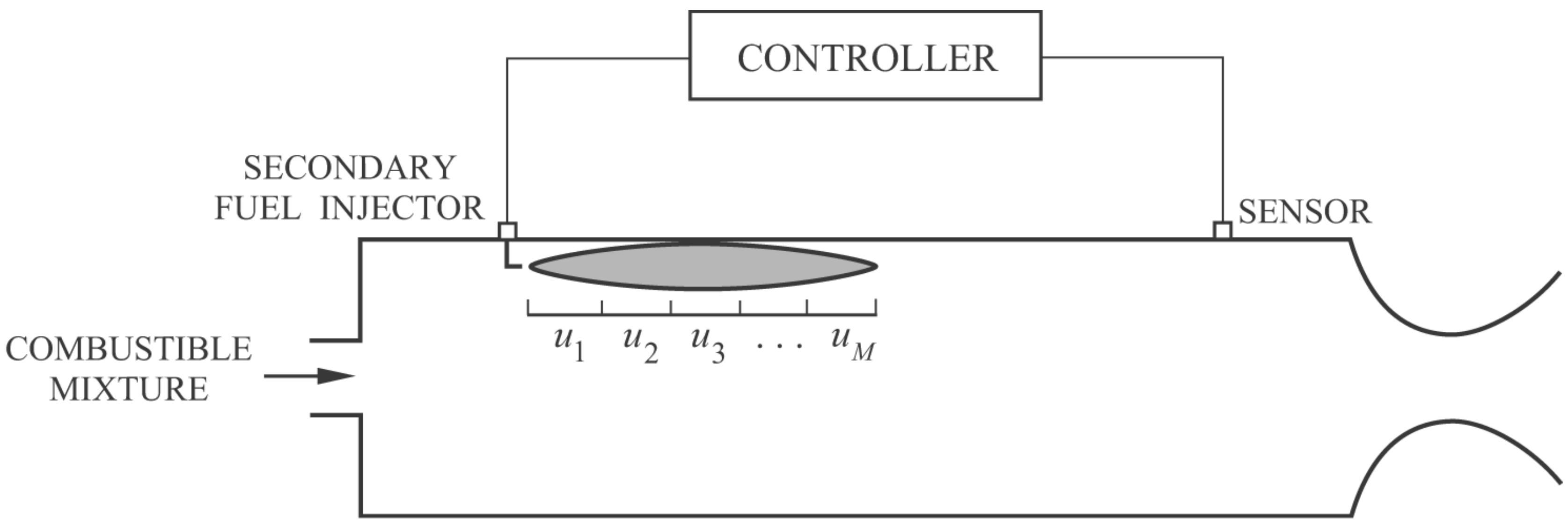
(*i*) No control

(*ii*) With control

A General Scheme for Connecting the Physical System, Modeling, Dynamics and Control



Simplified Sketch of the System Analyzed By FUNG et al. (1991)



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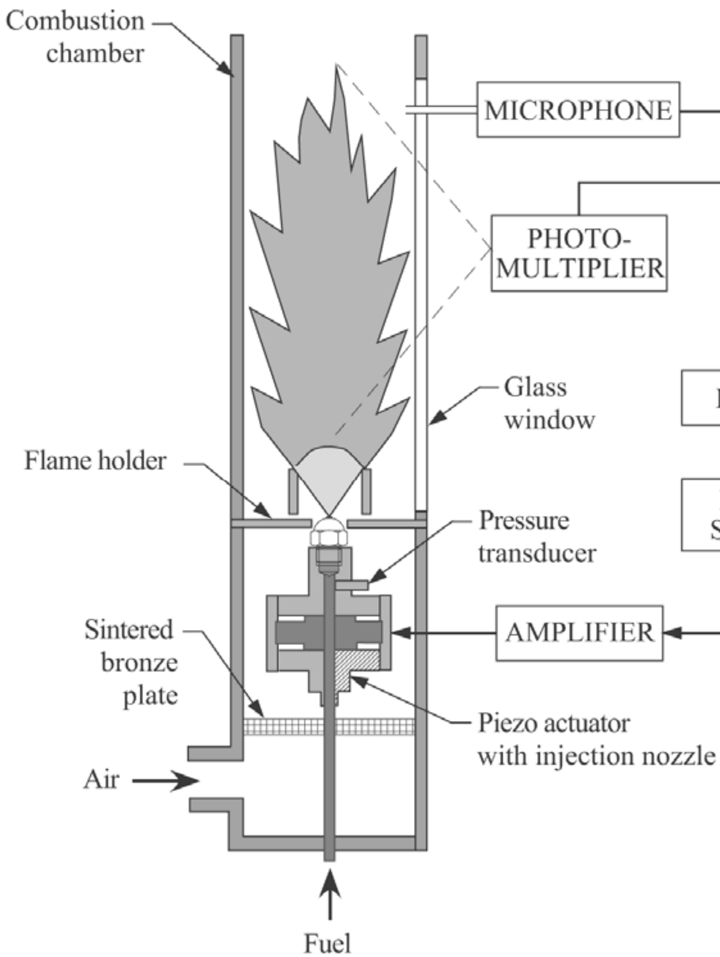
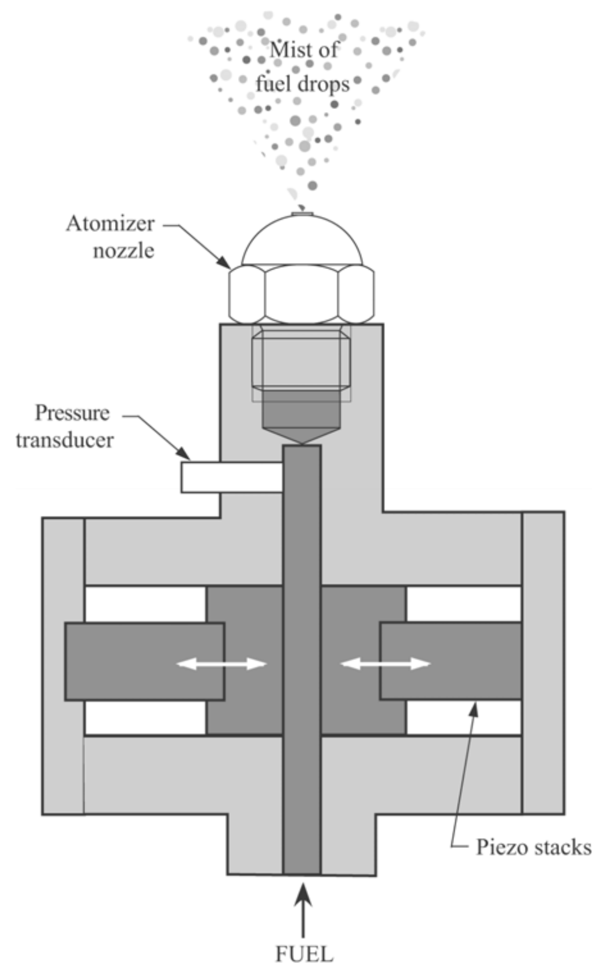
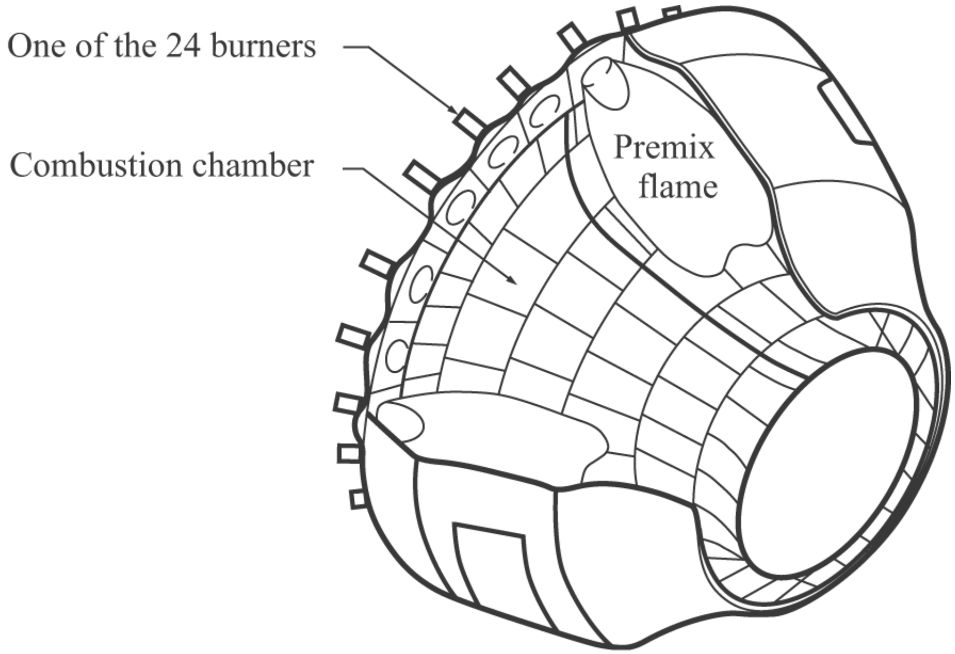
Feedback Control at Technische Universität München (HERMANN et al. 1996)

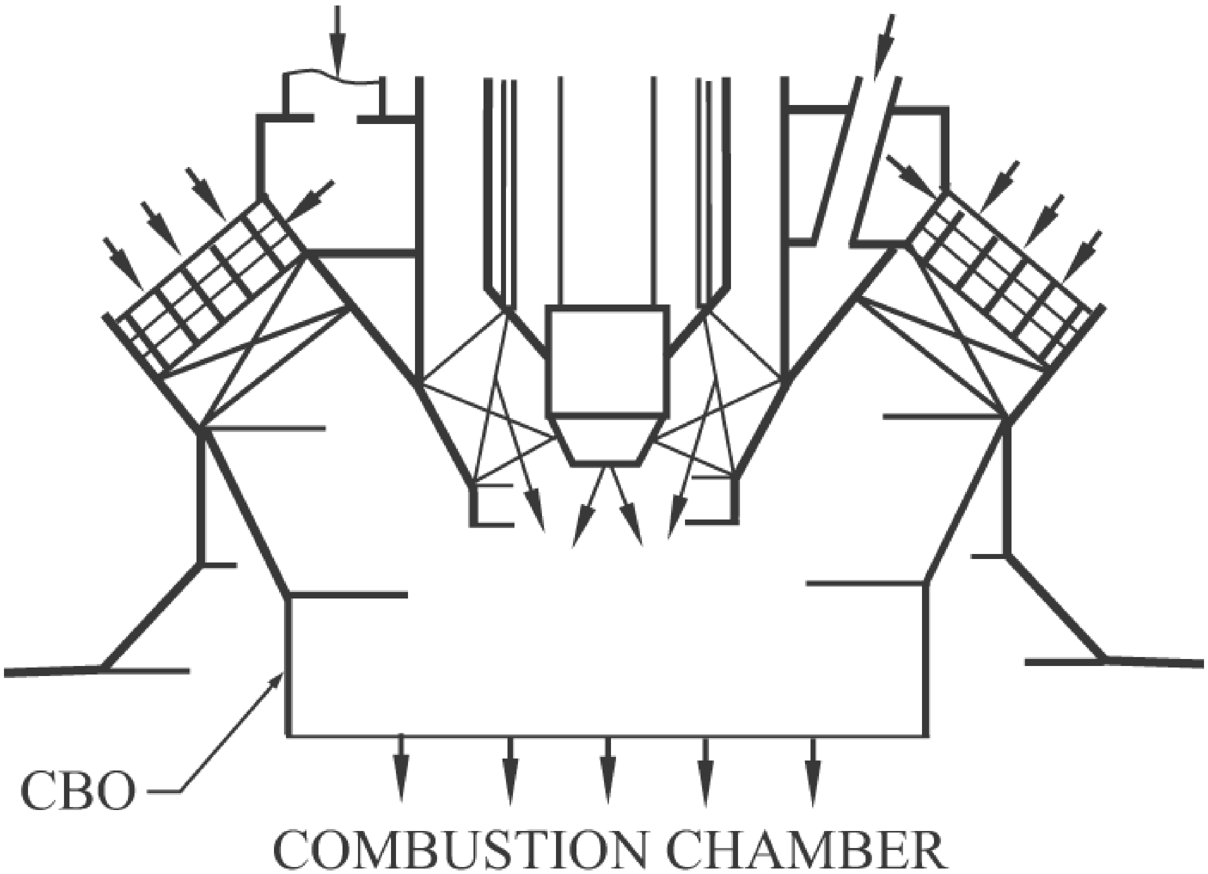




Application of Results by Hermann et al. to the Siemens Machines



Doing Away With Active Control of the Siemens Machines (BERENBRINK and HOFFMAN 2000)



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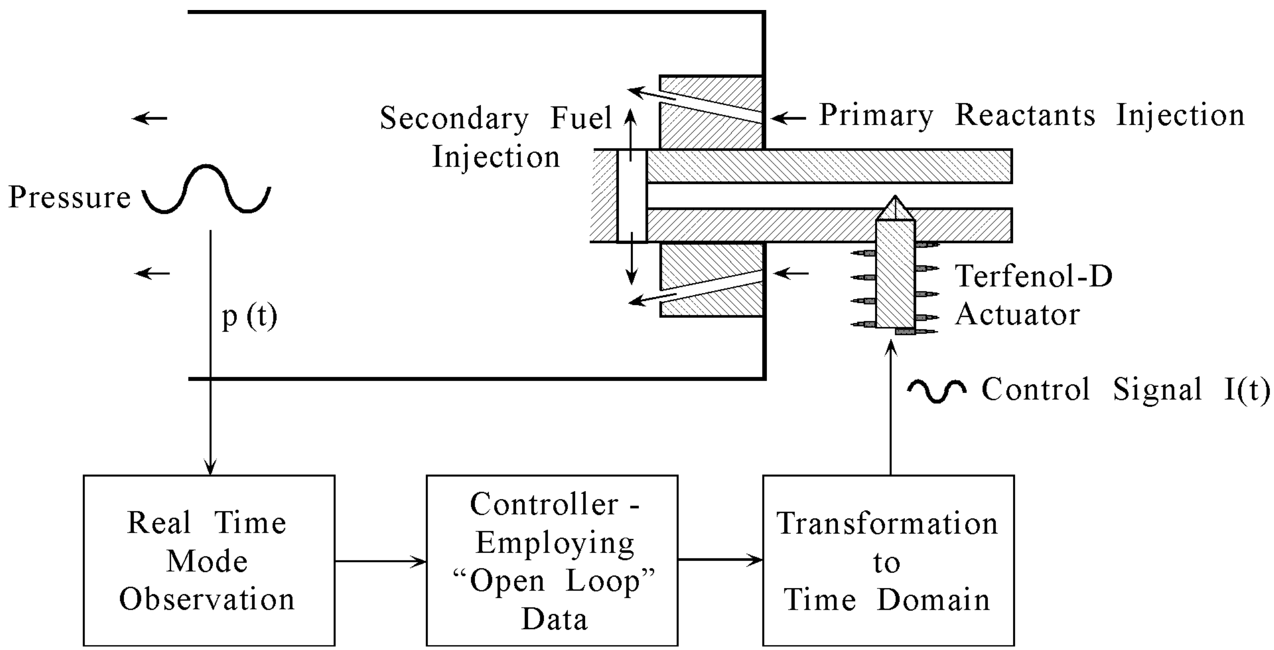
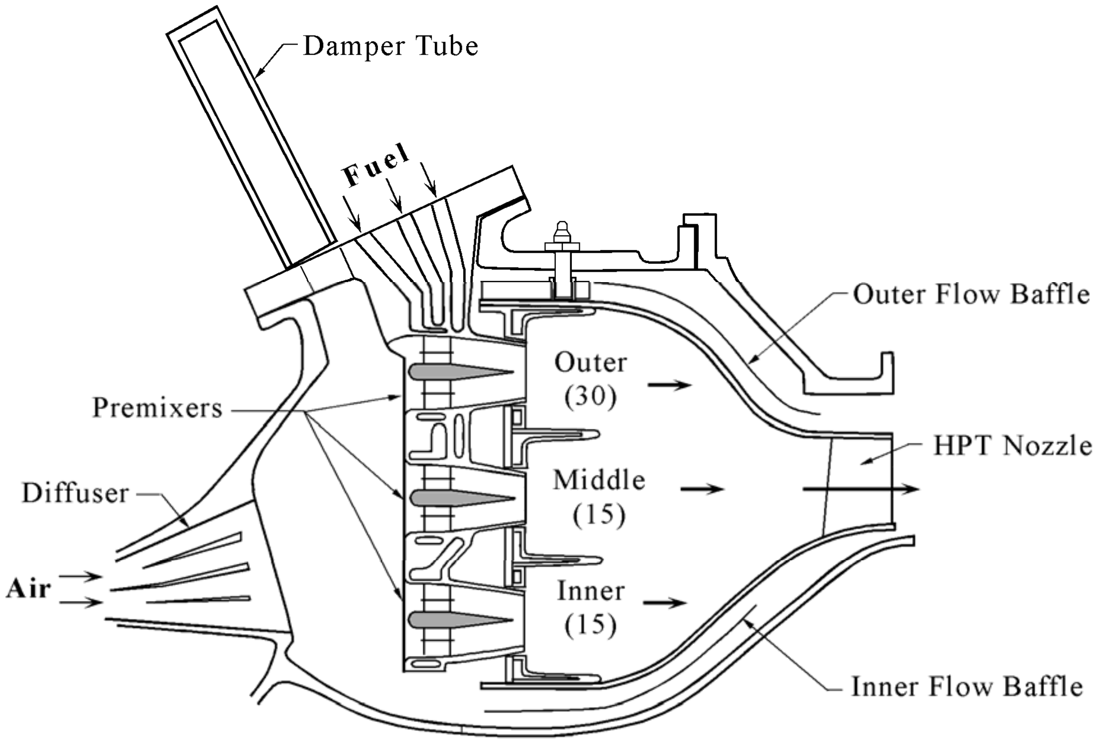
Georgia Tech Scheme for Active Control



- Real-time 'observer'
- Magnetostrictive Actuator

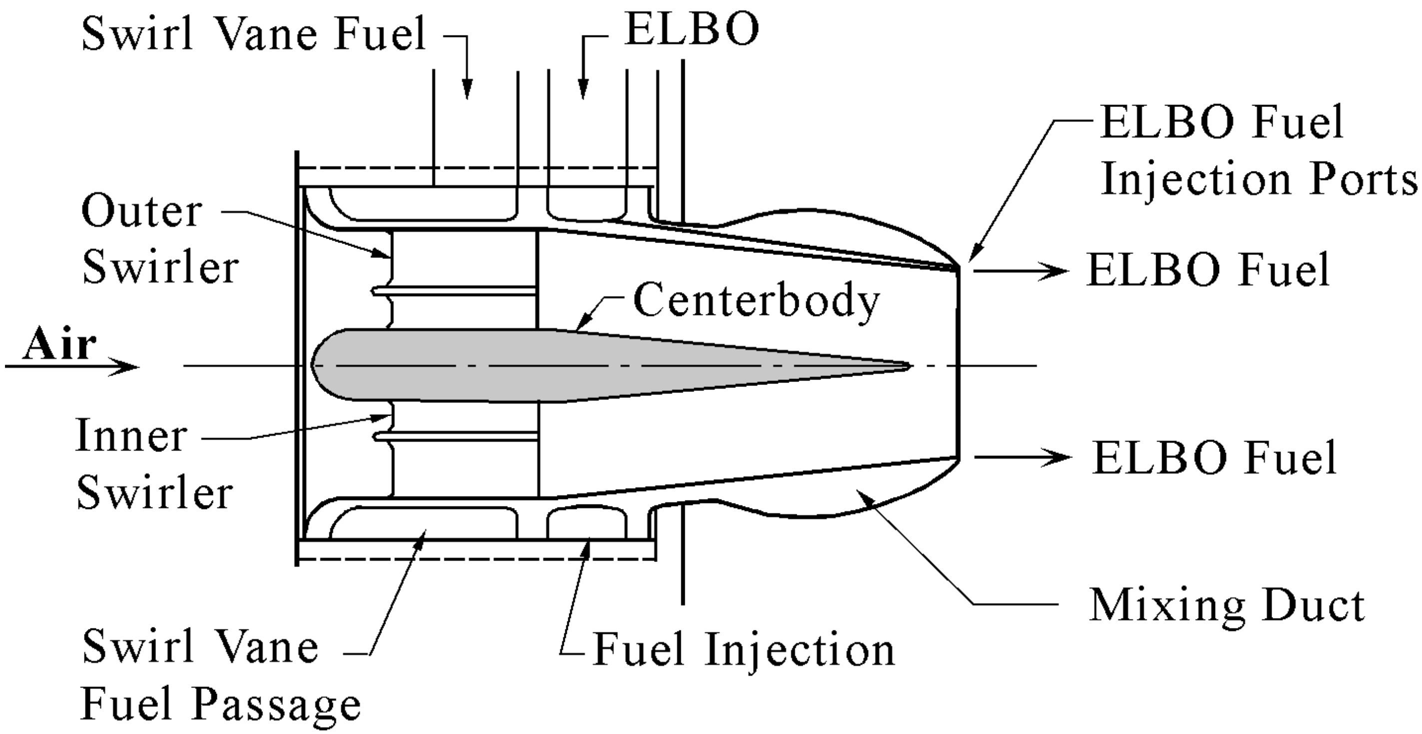
GE Dry Low Emissions (DLE) Combustor (LPP, Lean Prevaporized Premixed System)



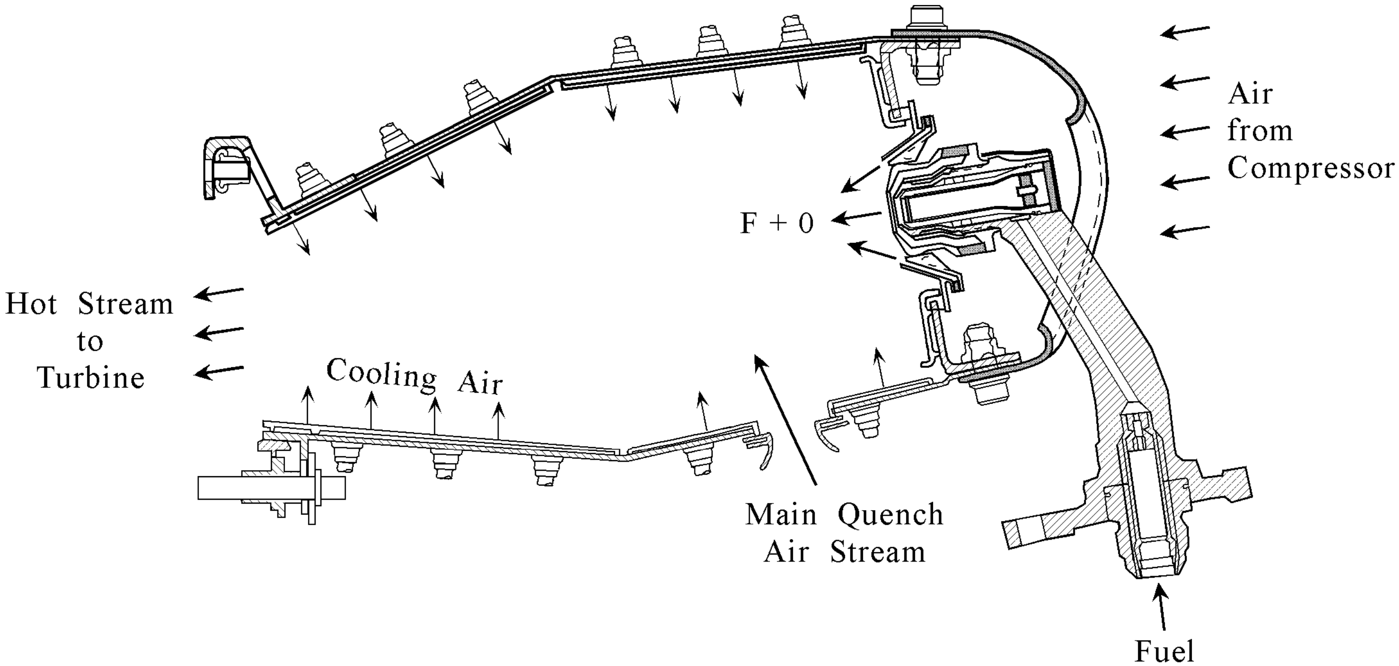
Swirlers are integral in several places

- Parametric control of instabilities

GE DLE 'Premixer' with Extended Lean Blowout (ELBO)

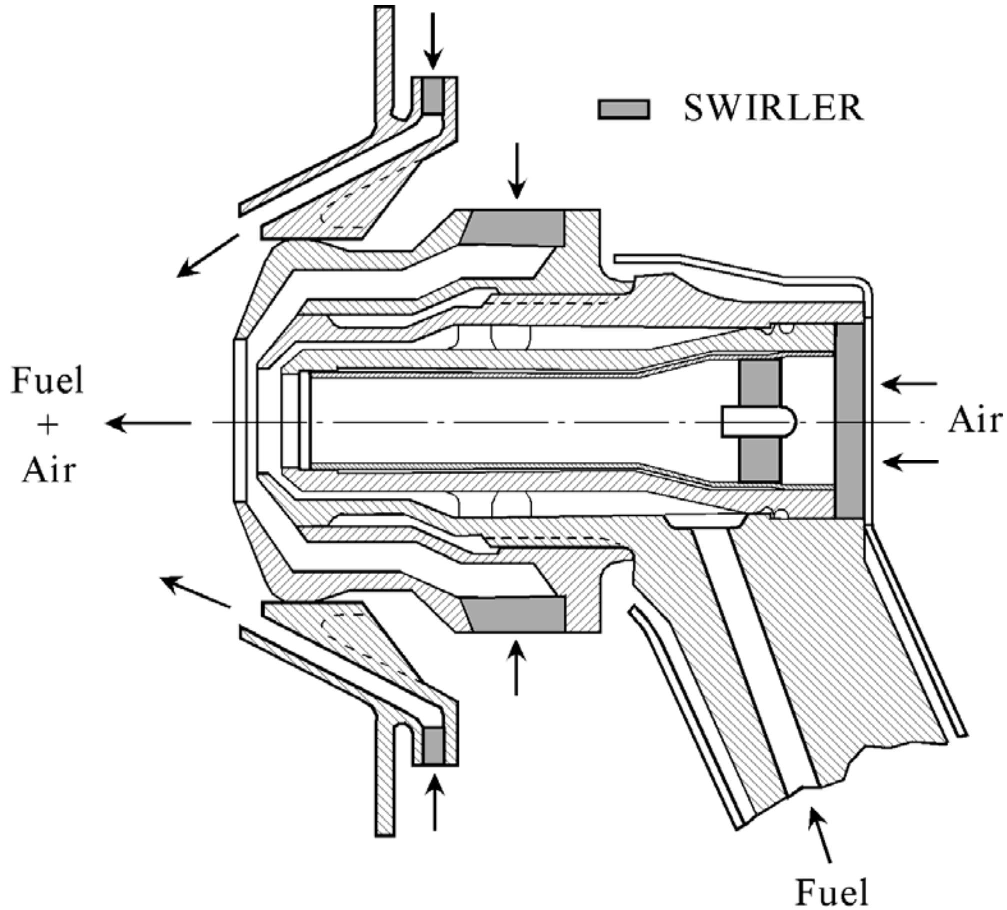


Pratt & Whitney Talon II Combustor (RQL, Rich Quench Lean System)

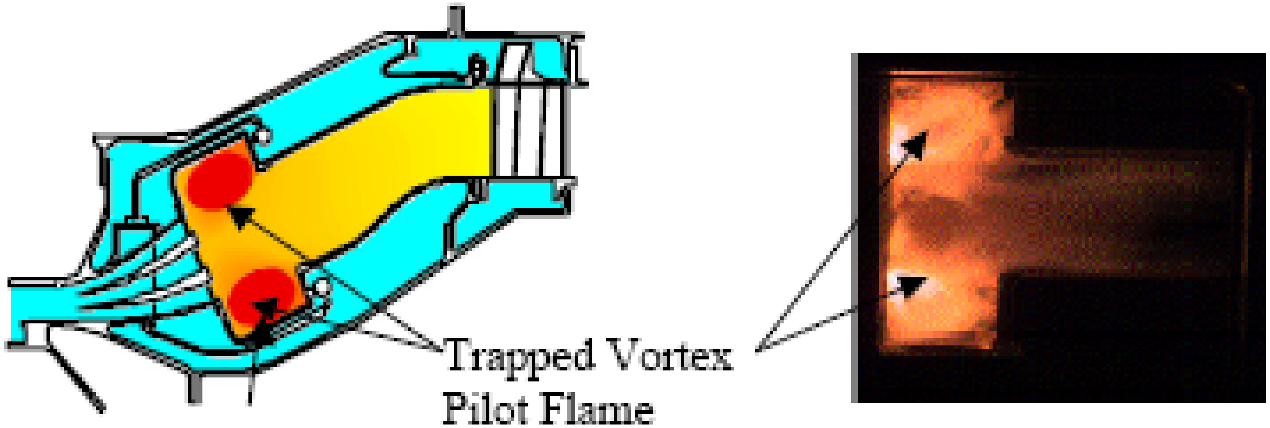


- Integral swirlers; swirl introduced with quench stream and cooling air
- ‘No’ problems with instabilities
- Rich Quench Lean (RQL) combustor

Pratt & Whitney Talon II Injector



The Trapped Vortex Combustor



- Concept first discussed at AFRL in 1993
- Combustion is sustained by a vortex trapped in a cavity near the injection plane

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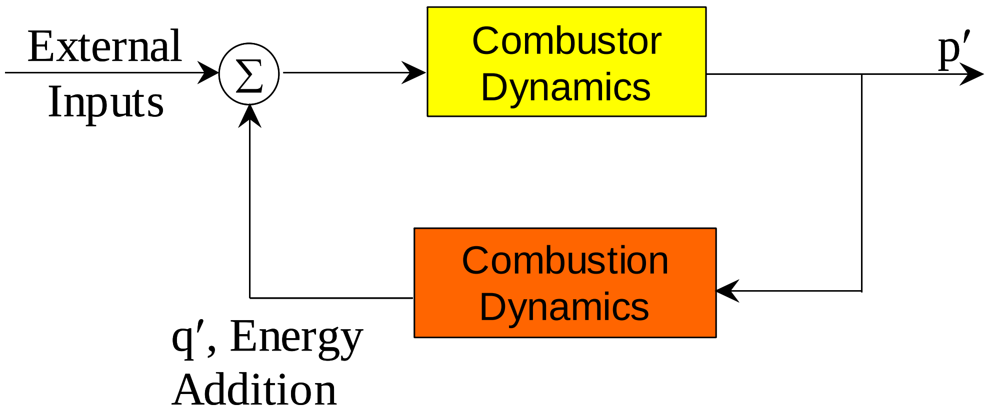
Motivation for Experiments

- The combustion response function is measured by artificially applying an oscillating pressure field and measuring the fluctuating heat release using either chemiluminescence or species specific PLIF.



Combustion Response Function

$$H(s) = \frac{q'(s)/\bar{q}}{p'(s)/\bar{p}} \quad ; \qquad s = j\omega$$

PLIF versus Chemiluminescence

What are the advantages of using PLIF versus chemiluminescence for measuring the time varying behavior of unsteady flames?

PLIF:

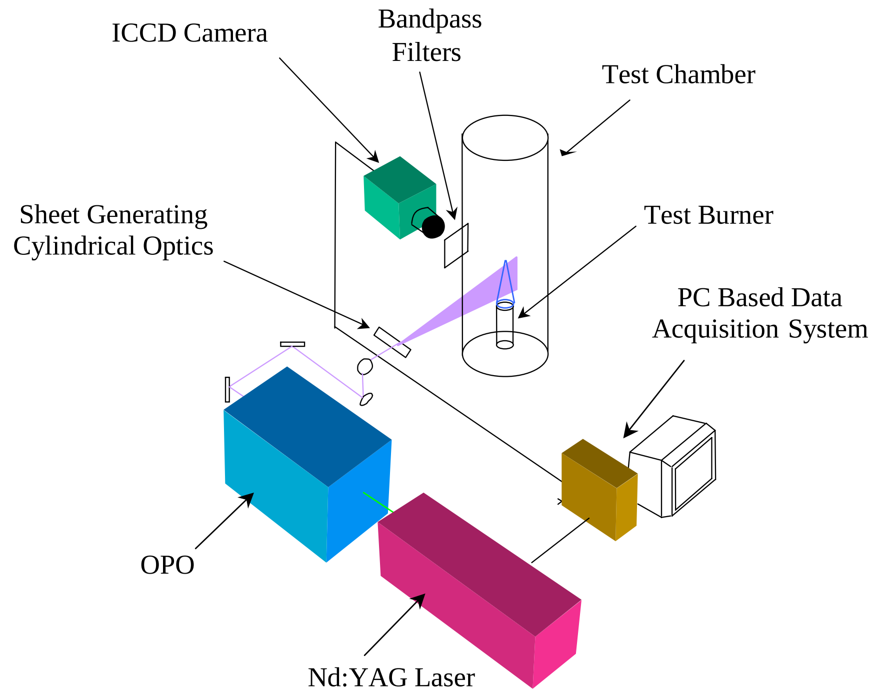
- Typical resolution is 60 um square in the plane normal to the imager and 500 um in depth.
- Short integration time for better temporal resolution (~50 ns).
- Can be used for quantifying unsteady heat release and unsteady concentrations of specific species (OH, NO, CH, CH2O, etc).
- Much higher cost and complexity. More technically challenging.

Chemiluminescence:

- Line of sight measurement. Small depth of field and imaging smearing, giving poor spatial resolution.
- Longer integration time (~200 μs) possibly of the same order as unsteady features in the flame.
- Only measures sum of passive emission from multiple species (i.e. CO2, CH, C2, OH).
- Low cost and complexity. Technically robust.

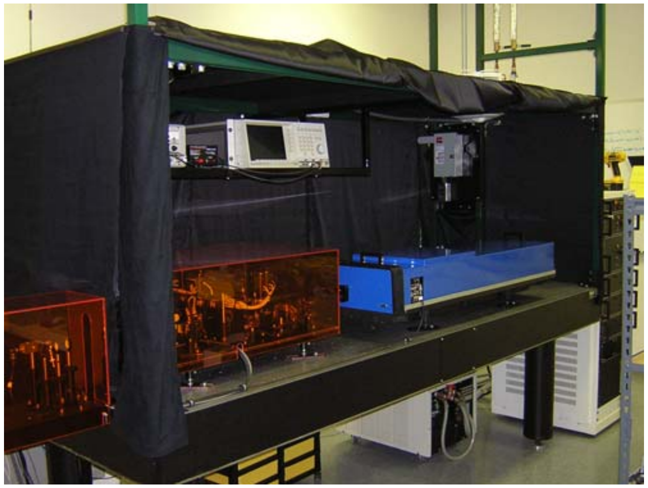
Experimental Arrangement for PLIF

- Controller uses pressure transducer to keep the p' amplitude at the flame constant.
- Nd:YAG pumped OPO generates tunable UV light for stimulating emission for select species (PLIF).
- Emission is detected with an ICCD camera.

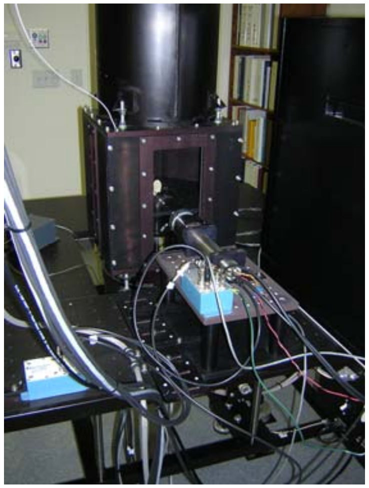


Laboratory

Combustion test section with acoustic forcing system.



Nd:YAG pump laser and custom built optical parametric oscillator (OPO).

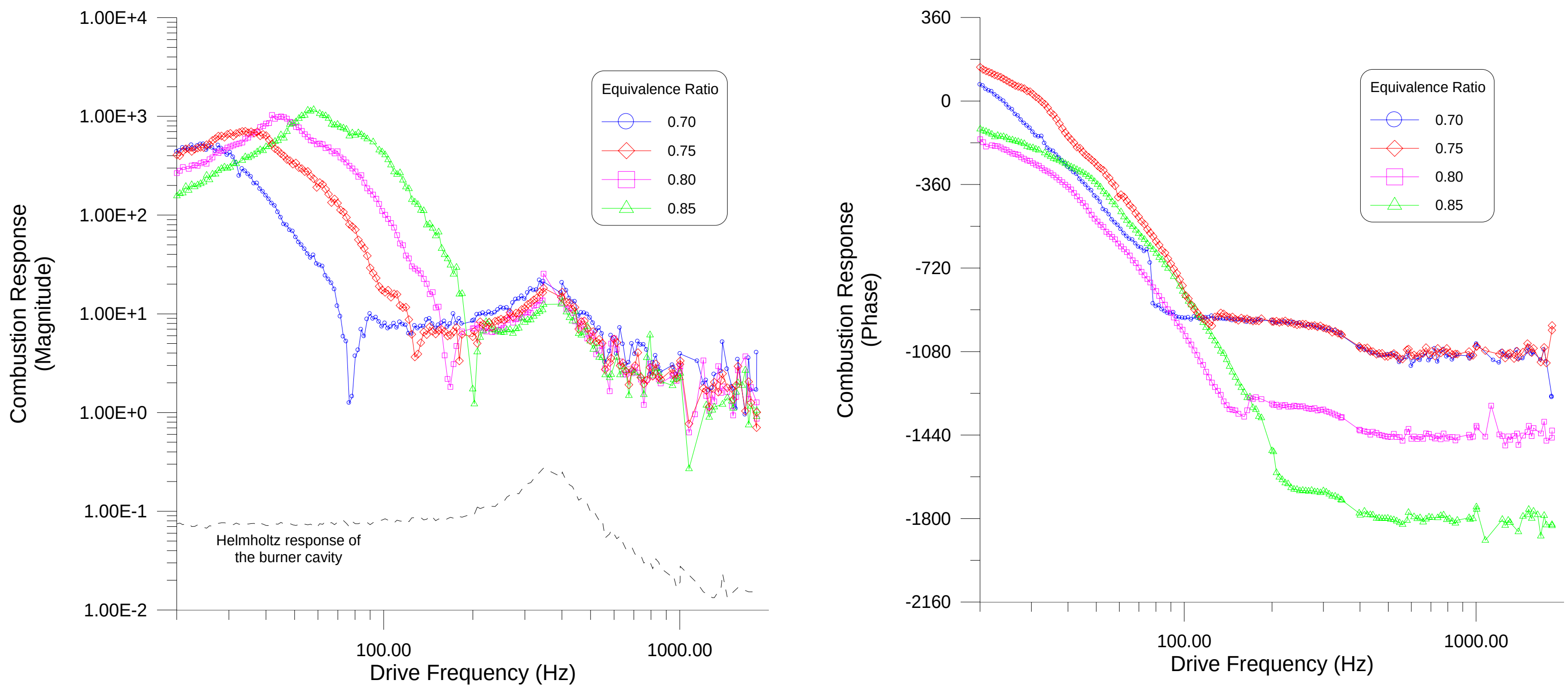


PMT collection system peering into test section.

Experimental bluff-body stabilized flat-flame burner assembly.

Typical Chemiluminescence Results

Bode Plots for the Combustion Response



- Combustion response function for acoustic forcing of a stagnation plane stabilized flat-flame burner.
- Graphs depict behavior at varying equivalence ratios with flame strain rate held roughly constant.

Peculiarity of Results

- Why is the peak response of the system between 20 Hz and 100 Hz? Feed system coupling in the presented system is not an issue since the premixed reactants are injected into the burner through a sonic valve. The burner cavity Helmholtz frequency is on the order of 350 Hz.
- What do the notches in the amplitude responses correspond to?
- Why do the phase plots roll-off as they do? These look like phase plots for a time delay, yet their rate corresponds to no time constant in the system.

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- Combustion systems are easily made to be unstable and the effectiveness of active control may be readily—and therefore misleadingly—demonstrated.

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- Active control can be an extraordinarily important tool for investigating the dynamics of combustion systems.
- But it is not a substitute for understanding why a combustion system is unstable.
- Combustion systems are easily made to be unstable and the effectiveness of active control may be readily—and therefore misleadingly—demonstrated.
- Is it true that if the dynamics of a practical combustion system are thoroughly understood, then the system may be designed to operate stably?