# Active Control of Combustion Instabilities in Low $NO_X$ Gas Turbines*

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### Abstract

The objective of this program, initiated in September 1995, is to investigate active control of detrimental combustion instabilities in low $NO_X$ gas turbines (**LNGT**) that burn natural gas in a lean premixed mode. The program consists of the following three tasks: 1. experimental investigations of the mechanisms that drive combustion instabilities in LNGT, and the effectiveness of various active control systems (**ACS**), 2. development of theoretical models that can predict the onset of combustion instabilities in LNGT and serve as a platform for studying the performance of various ACS for LNGT, and 3. interactions with industry. This abstract describes the progress made under this program during its second year.

The development of a LNGT simulator (the **LNGTS1**) that will be used to investigate the mechanisms that drive combustion instabilities in LNGT and to evaluate the performance of various ACS is near completion. The setup consists of an air inlet tuning section whose length can be varied to change the natural acoustic modes of the system, a premixing section where natural gas and air are mixed prior to entering the combustor section, swirlers for enhancing the mixing of the air with the fuel in the mixing section and the reactants with hot gases in the combustion zone, a combustor section with windows that will be used for flow visualizations and optical measurements, an exhaust nozzle and a rotary exhaust valve for driving pulsations within the combustor. The system also includes ports for installing the fuel injector actuators that will modulate the flow rate of a secondary fuel stream into the combustor to control instabilities.

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An investigation of the effect of the location of the fuel injector actuator (of the ACS) relative to the location of the primary combustion zone, and the design of the primary injector and actuator upon the performance of the active controller was performed in a gas rocket combustor (i.e., the **LNGT2**) that was retrofitted with a sub-scale version of the injection system of the LNGT. An open loop control investigation showed that a larger response is attained when the modulated secondary fuel stream is injected directly into the primary combustion zone. It was also shown that the open loop response of the fuel injector strongly depends upon the design of the actuator and the primary reactants injection system. These results have been used to guide the design of the LNGT1.

Work reported last year suggested that the presence of equivalence ratio perturbations (i.e., unmixedness) in the reactants stream entering the LNGT's combustor may drive large amplitude instabilities under lean operating conditions. Specifically, it was shown that small equivalence ratio perturbations produce very small and very large amplitude combustion process heat release oscillations in stoichiometric and lean mixtures, respectively. It was noted that if acoustic oscillations can produce periodic equivalence ratio perturbations by interacting with mixing processes and/or the reactants feed systems, the resulting heat release oscillations, when properly phased, would drive combustion instabilities in LNGT. These results motivated the development of a model for predicting the stability limits of LNGT. The developed model accounts for the interactions of the acoustics of the combustor, inlet duct and reactants feed lines with the flow processes and chemical kinetics. These interactions couple the combustor's pressure oscillations with equivalence ratio perturbations, resulting in a feedback mechanism that produces heat release rate oscillations.

The model consists of several regions; the air inlet duct, fuel feed line, a mixing section, dump plane, a combustion region where reactions are completed, and a post-combustion region that includes the exhaust nozzle. In this model, pressure perturbations in the combustor produce air and fuel flow rate fluctuations that generate equivalence ratio perturbations that convect toward the combustor. Upon reaching the combustion zone, these equivalence ratio fluctuations induce heat release rate oscillations that, in turn, generate pressure oscillations. The stability limits of the LNGT are determined by determining ranges of design parameters and operating conditions for which the LNGT is linearly stable/unstable.

Using the model, stability maps have been generated for ranges of combustor operating conditions that subsequently will be compared with experimental results to assess the validity of the model. The model has also been used to elucidate the relationship between system design parameters and characteristic times that lead to the initiation/suppression of combustion instabilities, and to develop "combinations" of design parameters that optimize the combustor stability. Significantly, the model predicts that under typical LNGT operating conditions, combustion instabilities can occur only when the time required to convect the mixture from the fuel injector to the combustor approximately equals one half of the acoustic period. This prediction agrees with recent experimental results obtained at FETC, and suggests that the developed model contains the essential ingredients of the mechanism that drive instabilities in LNGT.

Contacts have been made with several major gas turbine manufacturers to establish channels of communications that will keep us informed about problems that are of concern to industry and enable us to inform industry about our progress in the understanding and control of LNGT instabilities. To date, representatives from several gas turbine manufacturers have visited our laboratories to observe our active control capabilities. We have also had telephone contacts with representatives from other gas turbine manufacturers.

In support of a contract with a major gas turbine manufacturer, an available combustor was used to investigate the performance of various active controllers. The results of these tests were subsequently used to guide the design of an active control system that was tested on an experimental gas turbine combustor simulator at the manufacturer's facilities. Also, as part of this effort, members of our research team participated in an investigation of active control of combustion instabilities that was conducted at the gas turbine manufacturer's facilities. We are currently working with this gas turbine manufacturer in a cooperative effort that will develop an ACS for a full scale LNGT.

We supplied Dr. Pandalai from GE Aircraft with information needed to predict the acoustic properties of the LNGTS1. We obtained his predictions and will check their accuracy by comparing them with measured data as it becomes available.

Our future plans under this contract include: 1. completing the development of the LNGT simulator setup, 2. experimental investigations of the driving mechanisms and active control of LNGT instabilities, 3. the development of a linear model capable of describing the performance of the LNGT simulator, and 4. development of a heuristic model of an actively controlled LNGT that can be used to investigate the performance and optimization of various ACS.

# ACTIVE CONTROL OF COMBUSTION INSTABILITIES IN LOW $NO_x$ GAS TURBINE

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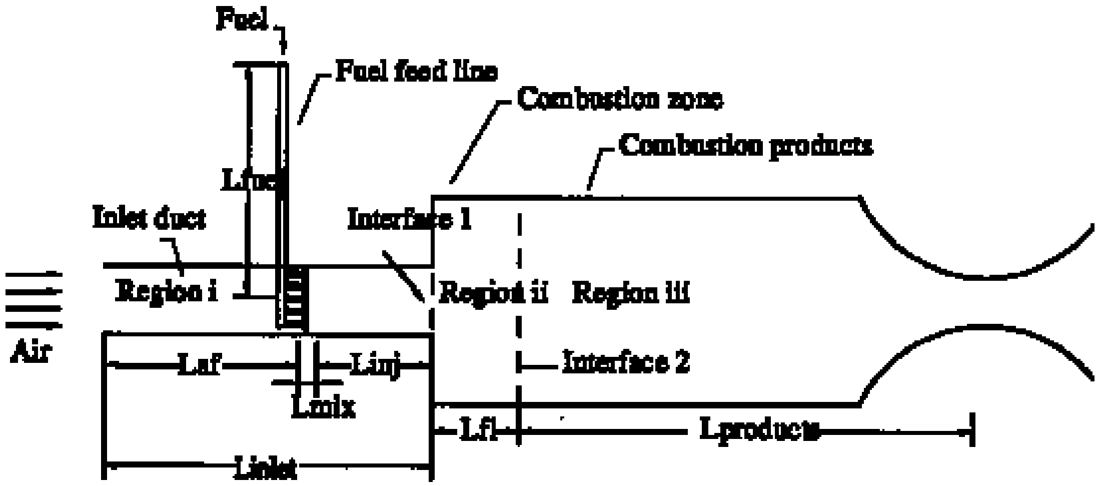
# PROGRAM OBJECTIVES

- Investigate the mechanisms that drive combustion instabilities in low $NO_X$ gas turbines
- Investigate active control of combustion instabilities in low $NO_X$ gas turbines
- Cooperate with industry to develop an active control system for full scale low $NO_X$ gas turbines

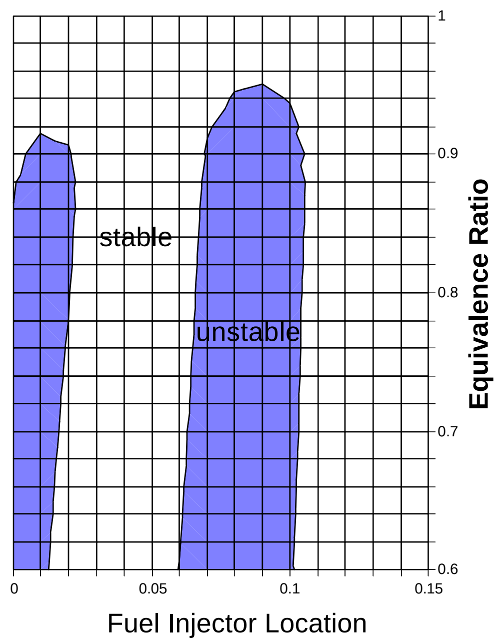
# Theoretical Prediction of Combustion Instabilities in Lean Premixed gas Turbines



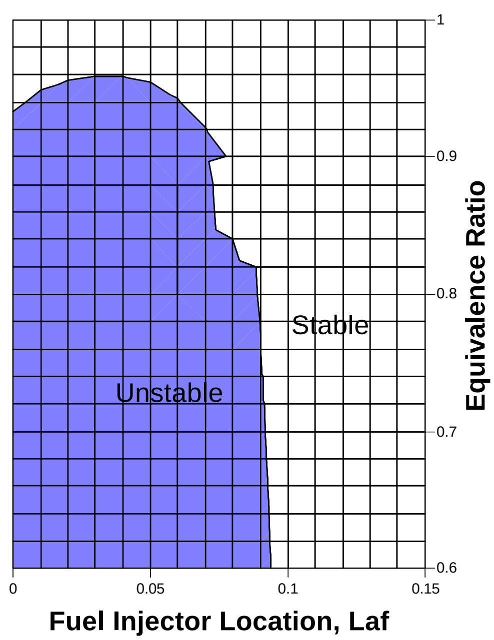

## Combustion Instability Mechanism

- Feedback between combustion chamber, inlet duct and fuel feed line oscillations
- Periodic variations in reactants equivalence ratio due to fuel feed line and inlet duct acoustics oscillations
- Combustion process heat release oscillations in response to the "transport" of the equivalence ratio perturbations to the combustion region

# Predicted Effect of Injector Location and Combustor Load on the Stability Limits

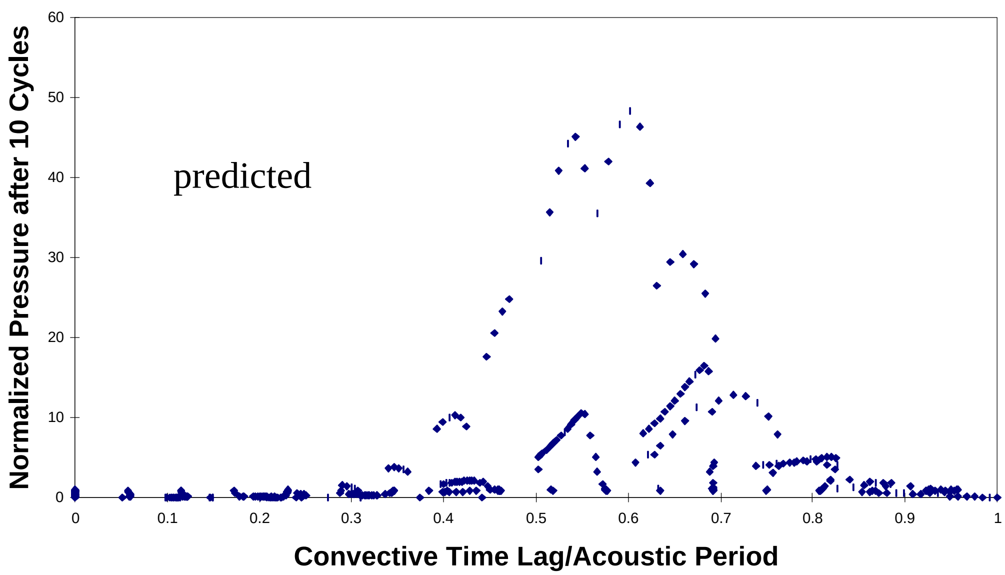


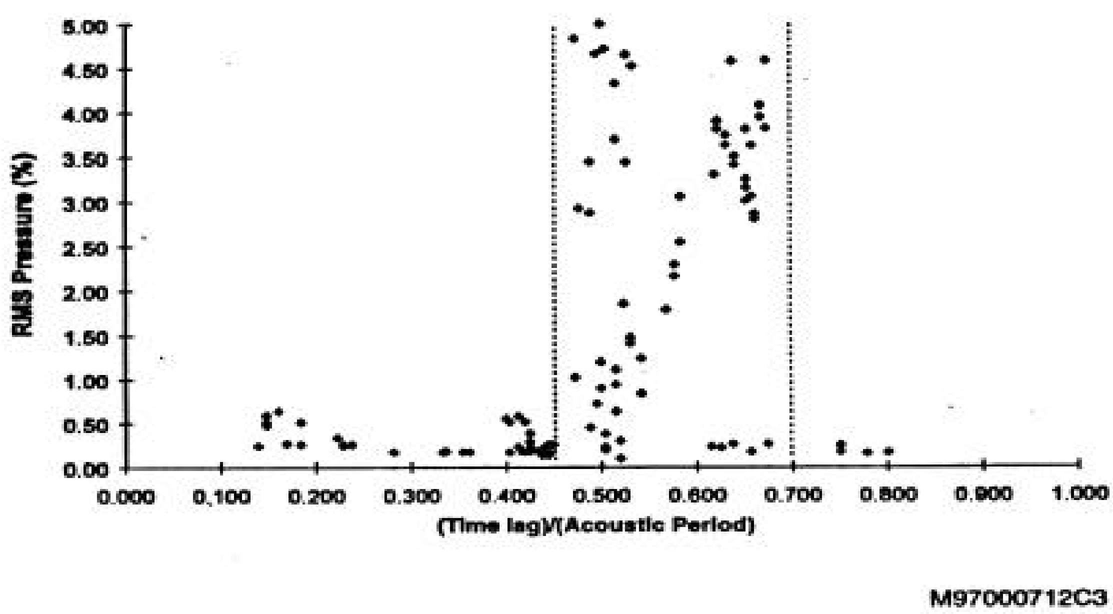

Low flow rate




High flow rate

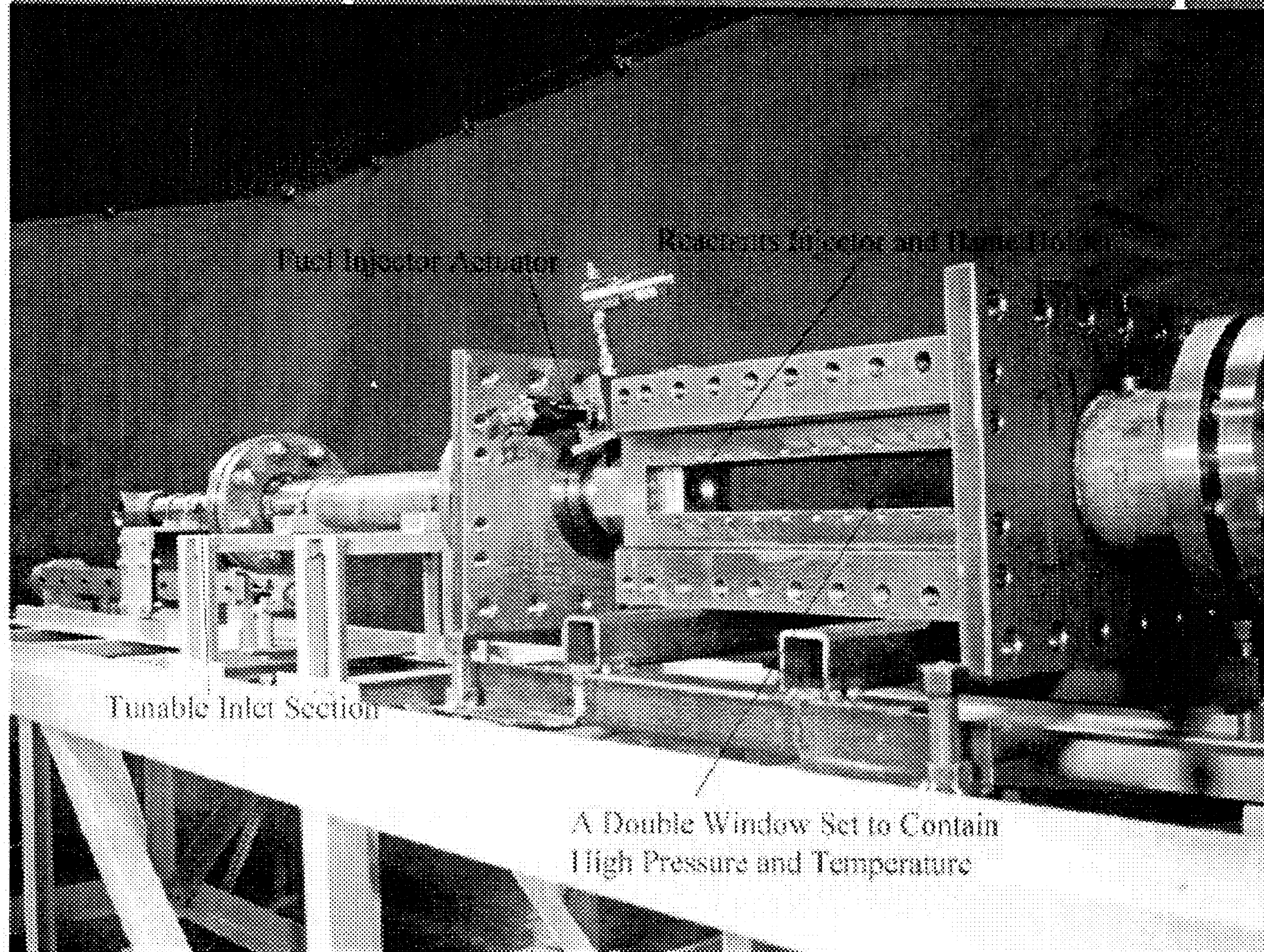
# Comparison of Model Prediction and Experimental Results



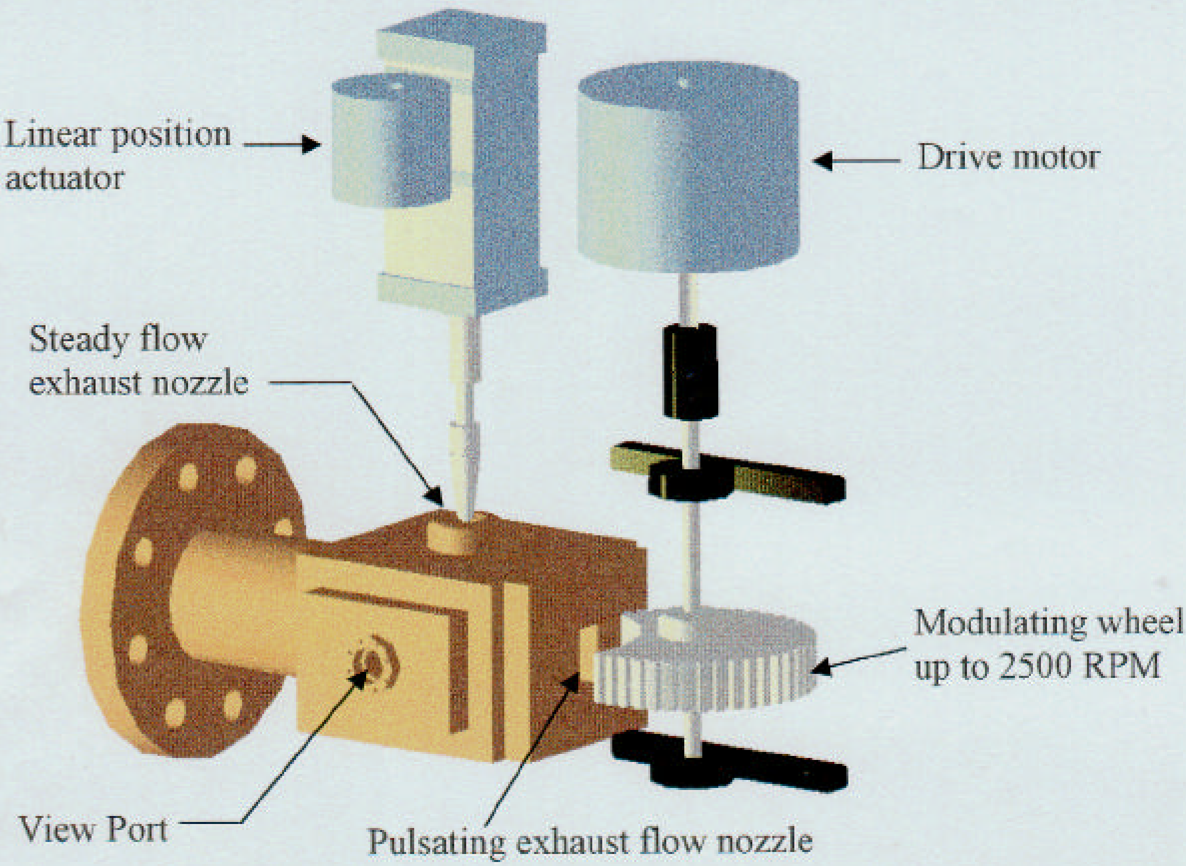




Obtained in the FETC Fuel Nozzle/Combustor (George Richards)

# Low $NO_x$ Gas Turbine Combustor Setup



# Exhaust Flow Assembly



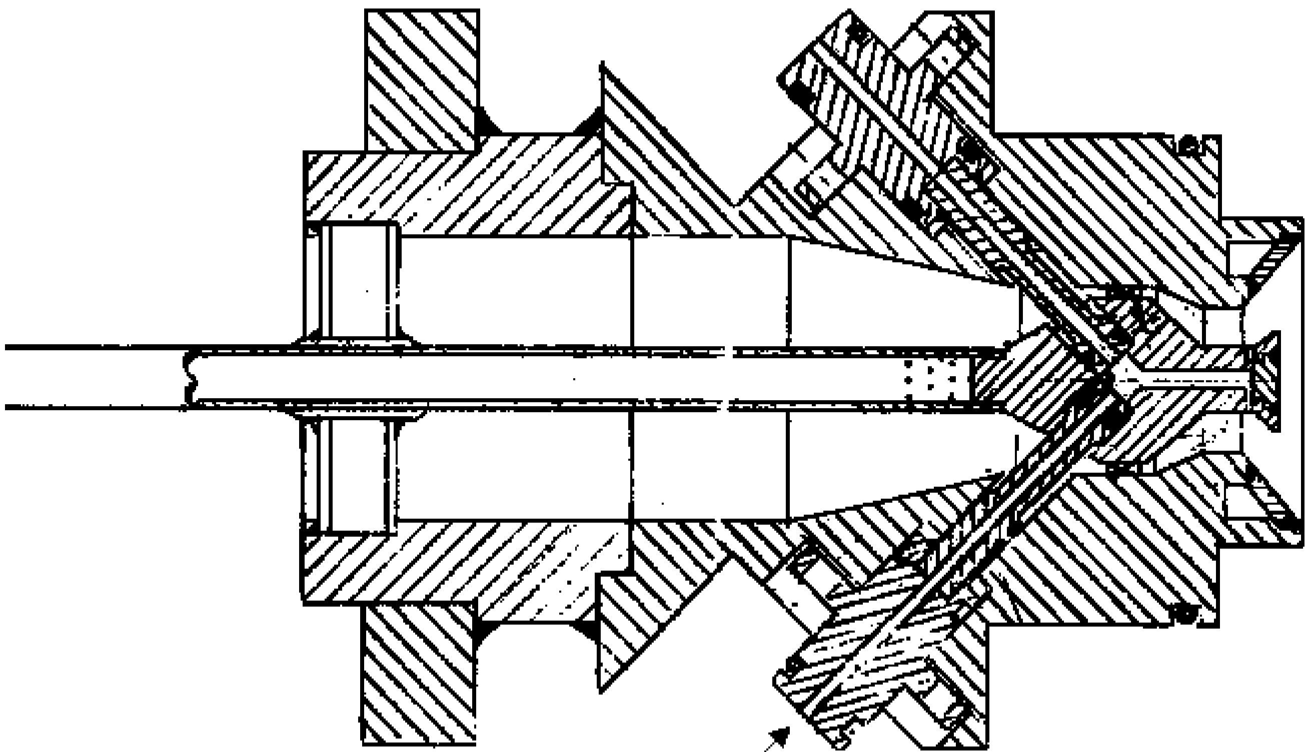

## Adjustable steady flow nozzle

- Controls mean pressure level in the combustor

## Forced pulsations:

- Determine the stability margin of stable modes
- Introduce persistent disturbances for control tests
- Enable multi-mode excitation control tests

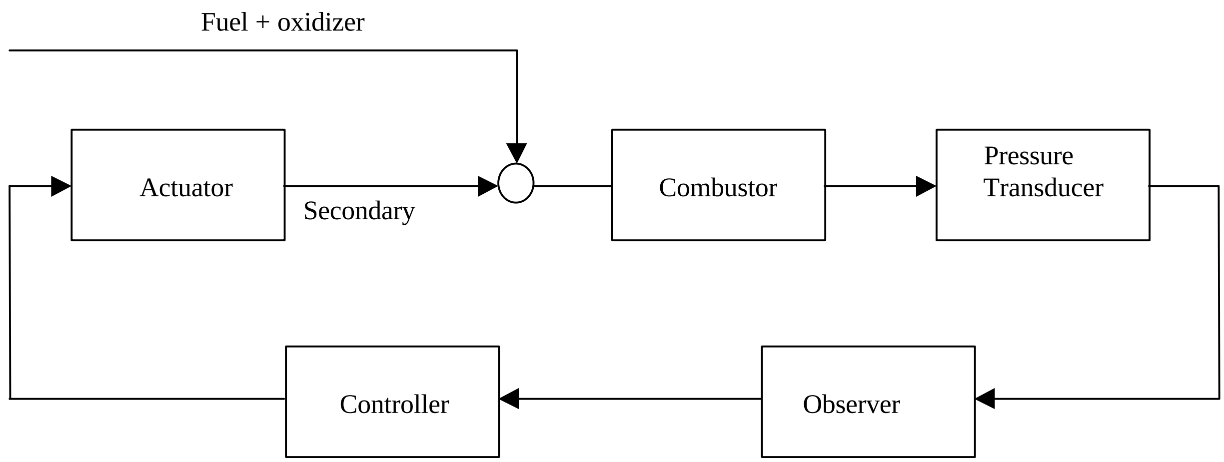
# Primary and Auxiliary Fuel Injection System




- High flow velocities in the injector to prevent flashback and auto ignition

- Two actuators modulate auxiliary fuel to control combustion instabilities

# Active Control System




## Theoretical and Technological Breakthrough

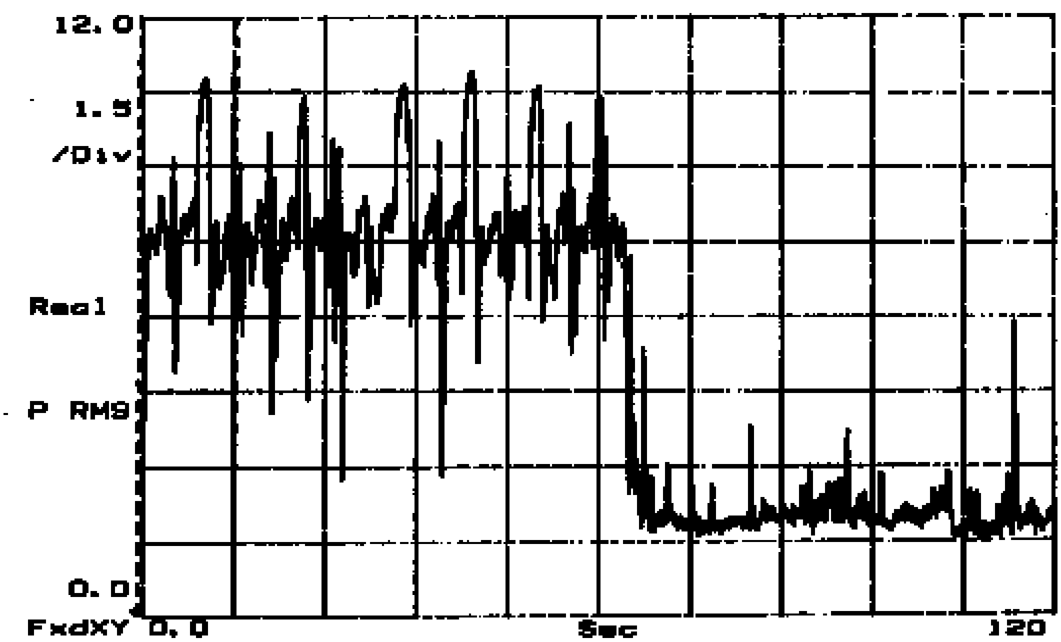
- Implement control approach based upon a novel observer
- Fast adaptive control to account for unknown combustor/injector characteristics
- Utilize a fuel injector actuator that modulates the fuel flow rate over a wide frequency range

## Practical Aspects of Control Approach

- Requires only a few pressure sensors
- Utilizes auxiliary fuel injection as a source of energy for attenuation of strong instabilities

# Interactions with Industry

- Application of the developed active control system for noise attenuation in a sub-scale, high-pressure lean premixed gas combustor at Westinghouse STC




RMS pressure level (psi) prior and after activation of the ACS

- Scale up of gaseous fuel injector actuator to flow rates up to 100 gr./sec for application in full scale gas turbines, is under development