Experimental Verification of Model-Based Control Strategies
Using a Backward-Facing Step Combustor

by

Adam D. Wachsman

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Signature of Author..........................

Department of Mechanical Engineering
May 18, 2003

Certified by..........................

Anuradha M. Annaswamy
Principal Research Scientist
Thesis Supervisor

Accepted by..........................

Ain A. Sonin
Chairman, Department Committee on Graduate Students
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ABSTRACT

Model-based control is a desirable strategy for reducing combustion instability because it is derived from an understanding of the physics responsible for the instability. This type of control scheme has evolved over the years to successfully control a range of experimental and full-size combustors. Model-based control depends on the ability to generate reduced-order models of the system in question. Proper Orthogonal Decomposition (POD) is a useful way of reducing the large amount of spatial and temporal information necessary for model-based control. Capturing this high resolution spatiotemporal data requires a new type of sensor, namely a linear photodiode array, capable of capturing linear spatial information at a high rate.

This sensor, combined with a POD-based adaptive PosiCast controller is tested on a backward-facing step combustor and an axisymmetric dump combustor. The actuator in the backward-facing step combustor is a high speed solenoid valve that forces air through a slot just upstream of the step. The result is an overall sound pressure level reduction of 6 dB when the combustor is operated at $\phi = 0.65$ and $Re = 8475$. The actuator in the axisymmetric dump combustor is a pulsed liquid fuel injector. An overall sound pressure level reduction of 6 dB is obtained when the combustor is operated at $\phi = 0.70$ and $Re = 30,000$.

Thesis Supervisor: Anuradha M. Annaswamy
Title: Principal Research Scientist
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1. Introduction

Continuous combustion systems, common in power generation and propulsion applications, are susceptible to the phenomenon known as thermoacoustic instability. Generally speaking, this instability is due to a self-sustained coupling between the acoustic field of the combustion chamber, and the heat release rate. Pressure oscillations inside the combustor cause a velocity fluctuation, which acts directly on the flame surface. The heat release rate is partly a function of flame area, so the heat release rate is modulated by the acoustics. This modulated heat release rate then provides more energy to the acoustic field. Rayleigh’s criterion states that when heat release rate perturbation is in phase with pressure perturbation, thermoacoustic instability can be sustained. This instability is undesirable because the large amplitude pressure and heat release rate oscillations lead to high levels of acoustic noise and vibration, as well as structural damage.

Thermoacoustic instability has become more pertinent as performance goals like reducing emissions become more stringent. For example, an effective strategy for combating a class of pollutants known as nitrous oxides (NO\textsubscript{x}) is to operate a lean premixed prevaporized combustor (LPP). Because NO\textsubscript{x} forms during high temperature combustion, a lean combustor lowers the maximum burning temperature, and therefore reduces NO\textsubscript{x}. However, it has been observed that LPP combustors experience combustion instability at their lean limit. Strategies for controlling the instability will increase the lean range that these combustors can operate in, and therefore lead to greater emissions reduction.
Active control of combustion instability is an attractive method to achieve performance goals, such as reduced overall sound pressure level, reduced emissions, and increased efficiency. The active control input used most commonly is fuel modulation. Early active control attempts commonly consisted of a phase-delayed version of the pressure sensor as a signal to a fuel injector. Heckl used this technique to reduce the dominant acoustic mode in a Rijke tube\(^1\). Hantschk used the signal from a microphone installed in a 137 kW liquid fueled combustor as feedback to a filter, followed by an analog phase-shifter to create an antiphase signal to a high speed valve to force the heat release rate fluctuations out of phase with the pressure, reducing the magnitude of the dominant frequency (but exciting a harmonic)\(^2\).

A less common active control input is modulation of air. This is used less often since it has a limited gain compared to fuel modulation, which can generate a much larger unsteady heat input. McManus et al used spanwise air forcing on a two dimensional dump combustor to reduce pressure fluctuations by forcing the inlet boundary layer\(^3\). Padmanabhan et al added crossflow jets to this system to simultaneously control volumetric heat release. Pressure was used as a feedback signal in addition to a one-


second moving average CH* chemiluminescence as a heat release measurement from fifteen individual photodiodes⁴.

Design of an active controller contains three parts. The first is the selection of a suitable active control input and an actuator that is a physical device that modulates control input. The second is the selection of a suitable sensor that measures key outputs of the combustion system. The third is the selection of a suitable strategy for modifying the control input as a function of the sensed outputs. The large field of control theory is by and large focused on this third part, where the strategy is designed based on a model of the combustion dynamics. The results reported in this thesis contain an air-based injector as an actuator with the mass flow rate of the air as the control input, for the most part. The sensor used is a linear photodiode array that measures the spatio-temporal distribution of CH* chemiluminescence in the combustor. The control strategy used is model-based and in particular, uses a POD model of the plant, and an adaptive PosiCast controller.

Several model-based control design results have been obtained in the literature. Some of them have been derived assuming that the pressure signal is composed of several sinusoids. A nonlinear observer was developed in this regard by Neumeier et al to track frequencies, amplitudes, and phases of the input signal and to predict future outputs⁵.

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Banaszuk et al assumed the same signal composition and used an Extended Kalman Filter to track the frequency, with an extremum-seeking algorithm to tune the phase.\(^6\)

A model-based control strategy is more advantageous since it is derived from an overall understanding of the coupling between combustion dynamics, hydrodynamics, and acoustics. A quantitative description of these mechanisms makes the problem amenable to optimization with respect to specific performance goals.

Model-based control strategy has been shown successful over the last several years. Fleifel et al demonstrated in 1996 that a combustion instability model based on flame kinematics under velocity perturbation was able to correctly predict experimentally unstable modes. In 1998, Hathout et al designed a linear quadratic regulator based on a dynamic model of a combustor. He demonstrated that by minimizing a cost function of unsteady pressure and control input, a wide range of pressure oscillation frequencies could be stabilized without energizing secondary peaks.\(^8\) Annaswamy et al used predictive model-based control design in 2000 to experimentally demonstrate that faster settling time and reduced control effort could be achieved on a 1 kW benchtop combustor controlled with a 0.2W loudspeaker.\(^9\)


As an alternative to reduced-order modeling described above, system identification has
been used to develop dynamic models based on input-output data. Brunell used system
identification to develop a model and model-based controller for a near full-scale
combustion rig under turbulent flow conditions\(^{10}\). Murugappan et al developed a system
identification model and a LQG-LTR model-based controller for a 30 kW swirl stabilized
spray combustor, and succeeded in reducing the overall sound pressure level 14 dB lower
than an empirical (non-model-based) phase-shift controller\(^{11}\).

Model-based control has been expanded to adaptive time-delay control as well. Time
delays are often significant in combustion systems due to the transport delay time
between fuel injection and fuel burning. Evesque et al developed a model-based adaptive
PosiCast controller that predicts future pressure response and uses an adaptive algorithm
to drive down the overall sound pressure level\(^{12}\). This adaptive PosiCast controller was
implemented by Riley et al on a swirl stabilized industrial gas turbine scaled rig\(^{13}\). Park et
al implemented the same controller on a liquid-fueled axisymmetric dump combustor\(^{14}\).

However, most of these investigations have focused on temporal response, neglecting
spatial information. One reason for this is the difficulty in processing high resolution

spatiotemporal data in real time. To address this problem, Proper Orthogonal Decomposition (POD) can be used to systematically extract the most energetic modes from a set of realizations from the plant model, and use the modes to compress the spatial information. The decomposition is "optimal" in that the energy contained in an N-ordered POD base is greater than any other N-ordered base in a mean-squared sense. POD was introduced independently by numerous people at different times\textsuperscript{15,16,17,18,19}, and has been variously referred to by various names including Karhunen-Loève decomposition, principal component analysis, and singular value decomposition. Over the years, it has been applied in several disciplines including turbulence in fluid mechanics, stochastic processes, image processing, signal analysis, data compression, process identification and control in chemical engineering, and oceanography.

In fluid mechanical systems, the POD technique has been applied in the analysis of coherent structures in turbulent flows and in obtaining reduced order models to describe the dominant characteristics of the phenomena. One of the earliest works was on a fully developed pipe flow, studied by Bakewell and Lumley\textsuperscript{20}. Since then, POD models have been used to model the one-dimensional Ginzburg-Landau equation\textsuperscript{21}, the laminar-

turbulent transitional flow in a flat plate boundary layer\textsuperscript{22}, pressure fluctuations surrounding a turbulent jet\textsuperscript{23}, turbulent plane mixing layer\textsuperscript{24}, velocity field for an axisymmetric jet\textsuperscript{25}, low-dimensionality of a turbulent flow near wake\textsuperscript{26}, low-dimensional leading-edge vortices in the unsteady flow past a delta wing\textsuperscript{27}, and flow over a rectangular cavity\textsuperscript{28}. The eigenfunctions were developed using both experimental and numerical databases.

Although POD has been used extensively in determining reduced order models of flow systems, relatively few attempts have been made to design active control strategies based on these models. Ravindran applied optimal control strategy to the reduced order model obtained from the finite element simulation of a backward facing step flow\textsuperscript{29}. Graham et al applied a similar technique to develop a reduced order model for cylinder wake\textsuperscript{30}, and used it to reduce the unsteadiness of the wake flow\textsuperscript{31}. Arian et al. showed the

convergence of the POD-based reduced-order technique in the presence of control input, by embedding it into the concept of Trust-Region (TR) methods, where the idea was to prevent the algorithm from exceeding a certain step size during each iteration, and thus guaranteeing convergence\textsuperscript{32}.

This thesis presents the results of real time POD-based control using a novel sensor on two different combustor designs. Chapter 2 presents the design of a backward-facing step combustor as a test-bed for model-based control. The combustor is instrumented with several sensors to interrogate the combustion process, including pressure transducers, mass flow meters, instantaneous equivalence ratio measurements, thermocouples, velocity sensors, high-speed Schlieren and CCD imaging, and a novel linear photodiode array used to extract high spatiotemporal resolution CH\textsuperscript{*} chemiluminescence data. Actuation includes high speed fuel and air valves for equivalence ratio modulation and hydrodynamics modulation near the step.

The high spatiotemporal resolution data from the linear photodiode array requires a method for compressing the data into a manageable size. Chapter 3 outlines how this is accomplished with the POD method. POD extracts the dominant mode shapes of the linear sensor image. In the images from the backward-facing step combustor, the first POD mode contains almost 70\% of the system energy. This chapter also describes how the scalar amplitude of this mode is generated and used as the basis for a system identification model relating air forcing to amplitude. Additionally, a technique for

recursively updating POD (RePOD) modes is presented. POD update is essential because POD modes change in response to control input. This is the first time POD has been used directly in a real time control loop.

Chapter 4 addresses the type of model-based controller used for stabilization, adaptive PosiCast. This controller predicts future outputs of systems with time delay using a Smith Controller, and then stabilizes the predicted system. This controller has been shown to be robust over a wide range of operating conditions in multiple combustors.

In Chapter 5, the results of control on a backward-facing step combustor are presented. The combustor’s unstable characteristics are discussed, with combustion instability noted over a wide range of operating conditions. The pressure and velocity cycles are compared with each other and to high speed CCD, Schlieren, and linear sensor images to determine the instability mechanism. POD is used to generate the POD mode amplitude for use in creating a system identification model, used to design an adaptive PosiCast controller. The controller is implemented and reduces the overall sound pressure level by 6 dB. This is compared to static air forcing at the same mass flow rate which increases the instability. Periodic air forcing is demonstrated at a higher instability level, and reduces overall sound pressure level by 24 dB, stabilizing pressure, equivalence ratio, and CH* chemiluminescence fluctuations. Finally, the results of a fuel forcing control experiment are presented, in which the overall sound pressure level is reduced by 10 dB.
The combination of RePOD, the linear photodiode array, and adaptive PosiCast control is tested on an axisymmetric dump combustor in Chapter 6. The combustor’s unstable characteristics are examined in a similar manner to the backward-facing step combustor described above. The overall sound pressure level is reduced by 6 dB, and the quarter-wave acoustic frequency is reduced to background noise level. Additionally, RePOD adaptation gain optimization is examined.

Emissions measurements are a valuable indicator of combustion control performance. Chapter 7 outlines the emissions sensor equipment installed on the backward-facing step combustor. Combustion instability has been addressed by control techniques. Analysis of emissions sensor data will determine the effect of control on other important performance goals such as NO\textsubscript{x} concentration, and combustion efficiency.
2. Backward-Facing Step Combustor

A backward-facing step combustor was built for use as an experimental test-bed for model-based control. The following describes the design of a 75 kW combustor, installed in MIT’s Active Adaptive Control Laboratory.

2.1 Design

2.1.1 Stabilization Concept

The design of the combustor is based on a backward-facing step used to stabilize the flame. The backward-facing step features a contraction region followed by a sudden expansion as shown in Figure 2.1. This sudden expansion causes a recirculation zone to form, which anchors the flame by providing local cooling, and by continuously igniting incoming reactants with high temperature products.

![Figure 2.1 - Backward-Facing Step Profile Schematic](image)

The flame is anchored by the recirculation zone behind the step.
Fuel burning occurs primarily in the shear layer, which flaps up and down (and can also flash back or blow out). Large scale vortices are shed during unstable combustion. The plane that the step lies in is defined as the dump plane. The height of the step (2 centimeters) is used as a normalizing dimension.

2.1.2 Contraction Section Design

There are two different contraction section designs. The first uses a short curved contraction section leading to the dump plane as shown in Figure 2.2. The second uses a ramp followed by a long contraction section leading to the dump plane as shown in Figure 2.3. The short contraction section was the first design, based on an analytical model of the flow to create a flat velocity profile at the dump plane[^33]. The second section was designed after flashback was experienced using the short contraction section.

![Figure 2.2 – “Original” Test Section Profile](image)

This profile was designed to create a uniform velocity profile at the dump plane.

2.1.3 Equipment

The air is supplied from an Atlas Copco GA30-125-FF stationary, single-stage, air-cooled, oil-injected screw compressor driven by an electric motor. This air compressor is the Full Features (FF) variant provided by Air Power of New England, and includes an integrated refrigeration dryer for a constant supply of clean, dry air, Atlas Copco’s Elektronikon monitoring & control system, and super silenced build-up. The motor power of this unit is 30 kilowatts (40 horsepower). The maximum working pressure is 882 kilopascals (128 psig) and the maximum volume flow rate capacity is 85 liters per second (180 cfm). This required wiring and installation of a 480V, 60A power line by the MIT Electrical Facilities Department.

The air exits the air compressor through a ball valve and travels through 1.5-NPT pipe, some of which is solid steel, and some of which is flexible braided stainless steel. This
assembly is connected to a 908 liter (240 gallon) receiver tank which is used to store the pressurized air. The compressor adds compressed air to the receiver tank until the pressure reaches the “unloading pressure”, at which point the compressor stops. The pressure drops in the tank as air is used, until the pressure reaches the “loading pressure”, at which point the compressor turns back on. Most experiments were conducted with an unloading pressure of 102 psi, and a loading pressure of 98 psi. Tighter pressure control is possible, but it seemed reasonable to relax the tolerance to extend the life of the compressor, and to prevent the temperature in the test cell from increasing too high from the heat rejected by the cooling air. The pressure is regulated to 50 psi later, so 98 psi and 102 psi are both reduced to 50 psi.

2.1.4 Air Delivery System

The air from the receiver tank is then routed to two Zander microfilters to remove oil and particulates from the air stream. The first one is a G112ZDF-HTNX 1.5” prefilter, followed by a G112XDF-HTNX 1.5” coalescing filter.

This is followed by a 1.5” ball valve before going to a series of flexible 1.5” stainless steel braided tubing. This connects the air supply to the main test section and is about 12 meters long. At one point, a tee (1.5” x 1.5” x 0.5”) is introduced to divert air to the air forcing valve described later (originally installed for window air cooling).

The flexible air line is attached to a bronze pressure regulating valve (#4946K95) from McMaster-Carr Supply Company that allows regulation within a 15-130 psi range. It is currently adjusted to regulate the 100psi supply down to 50psi.
After the regulator, the air passes through an elbow and 1.5” tubing. This is followed by a BadgerMeter Research Control normally-closed valve RCV-752 from Eastern Controls Inc. with 1” ports, described in the actuator section. The air is expanded back to 1.5” pipe, and is sent to the air mass flow meter, described in the Sensors section.

After the air mass flow meter, the air makes a 180° turn through 2 elbows. It passes through a pressure indicator, which is used to set the pressure on the brass pressure regulating valve. After this, the air flows through a 1.5” ball valve and into a custom stainless steel expansion section designed to expand the air from the 1.5” tube to the 4 centimeter by 16 centimeter square combustor tunnel.

The main section of the combustor rig is a rectangular welded stainless steel tunnel with a cross section 4 centimeters (2 step heights) in height and 16 centimeters (8 step heights) in the cross stream direction. This tunnel is approximately 1.87 meters long and is supported by 6 steel supports / brackets, 20 centimeters high on top of a test bench that is 76 centimeters high. The tunnel is divided into 3 sections: 1) intake, 2) test, and 3) exhaust.

2.1.5 Intake Section

The intake section connects the main air line to the test section (Figure 2.4). It was initially 62 centimeters long, but was later cut in half to allow greater flexibility in acoustic boundary modifications, like choke plates, and the flow straightener, both an acoustic damper and a turbulence reducer. In the current configuration, there is a choke
plate at the entrance to the intake section, and a no flow straightener. In the upstream intake section, there are ports (1/2-20) for a pressure sensor (Kistler 206) (37.8 step heights upstream of the step), and a TSI 1210 hot wire anemometer probe (34.55 step heights upstream of the step). In the downstream intake section there is a port for the old fuel injector (25.8 step heights upstream of the step) (1/4-NPT) and a port (M14x1.25) for another pressure sensor (P2, Kistler 7061B1 described in the Sensors section) (24 step heights upstream of the step). There are also two ports for the 0.25 inch (outer diameter) fuel injection tubes (28.3 and 17.5 step heights upstream of the step) in the side of the combustor.

Figure 2.4 – Intake Section
The intake section is divided in two, providing flexibility in boundary conditions.

2.1.6 Original Test Section

There are two different test sections that can be installed between the intake section and the exhaust section. Both are about 62 centimeters long. The first test section has a ramp
that gradually contracts from 4 centimeters to 2 centimeters, before suddenly expanding back to 4 centimeters (Figure 2.5). This sudden expansion is known as the dump plane. The shape of this contraction is based on an analytical function that results in a flat velocity profile at the dump plane. The contraction section begins about 16 centimeters (8 step heights) upstream of the dump plane. This section has many ports on it for measurements, fuel, and visualization.

There are 2 ports for the 0.25 inch (outer diameter) fuel injection tubes (9.5 and 5.75 step heights upstream of the step) in the side of the combustor. There is also a port on both sides that holds the optical sapphire (Al₂O₃) view port for the laser equivalence ratio measurement device described in the Sensors section (2 step heights upstream of the step). Further downstream is the main window, made of quartz from Bond Optics. The visible area of the quartz window is 4 centimeters (height) by 22 centimeters (streamwise). There is 2 centimeters (1 step height) visible upstream of the dump plane. This is used
for visualization and for light based measurements, e.g. the linear photodiode detector, and the high speed camera. The top of the combustor has a port for a hot wire anemometer probe (9.65 step heights upstream of the step). The next port (8.13 step heights upstream of the step) was initially for a pressure sensor (Kistler 7061B1, M14x1.25) but it was determined that pilot fuel was needed here, so a custom fitting was manufactured at MIT Central Machine Shop. This fitting is 14 millimeter positive to 0.25 inch compression tube fitting, and allows the connection of a 0.25 inch (outer diameter) fuel tube to the pressure sensor port. Next is a port for another pressure sensor (5.5 step heights upstream of the step), followed by a port for a hot wire anemometer probe 3.7 step heights upstream of the step). There is also a hole (center is 1 step height upstream of the step) for the igniter fitting that is 1 inch in diameter. Following this is a long slit for a window that can be used for particle image velocimetry (PIV). The visible area is about 17.5 cm x 1.8 cm. Next to this window is a port (1/2-20) for the heat flux sensor, above the flame zone. On the bottom of the test section is a heat exchanger that was designed to remove heat from the burning zone and transfer it to a water stream, as shown in Figure 2.6.
Additional cooling for the windows is provided by 6 \(\frac{3}{4}\)-NPT fittings above the quartz windows. A slot, 2 millimeters in width and 220 millimeters in length, on the inside of the window allows a curtain of air to blow down, cooling the windows. The air supply comes from the tee mentioned earlier. The air supply would then go to a ball valve via \(\frac{1}{2}\)-NPT flexible rubber hose and into a manifold for distribution to the 6 ports. This was later removed because natural window cooling was effective for the duration of a single test (approximately 60 seconds). The forced air also changed the characteristics of the flame, so this may be used for control in the future. These holes are currently plugged with \(\frac{3}{4}\)-NPT stainless steel plugs.

### 2.1.7 New Test Section

The second test section has a different approach to the dump plane (Figure 2.7). The original design with the Libby curve is susceptible to flashback at low air flow velocities. By design, there is a low velocity region, followed by a short high velocity region,
followed by another low velocity region where the flame is anchored. It seems that if the velocity fluctuations due to instability become large enough, the laminar flame speed actually exceeds the local flow speed at certain times, and the flame can “escape” upstream, through the short contraction section to the low velocity region upstream.

Figure 2.7 – New Test Section Design
This section features a longer contraction section to reduce flashback. Also visible are the Moog DDV, the linear photodiode array, and the equivalence ratio sensor.

Once there, it typically burns backwards and the flame becomes anchored at the fuel injector and turns into a diffusion flame. Therefore, a second test section was designed with a longer contraction section to keep the velocity high for a longer distance, and reduce flashback. The overall length of this section is 62 centimeters. This section has a linear ramp that is 7.6 step heights long that contracts the flow from 2 step heights to 1 step height. This is followed by a section that is 1 step height high for a distance of 8 step heights before the dump plane. The second test section also has a number of ports for measurement and optical access. The pilot line port (1/4-NPT) is 8.3 step heights
upstream from the step. A pressure sensor port (M14x1.25) is 5.65 step heights upstream from the step. A hot wire anemometer port is 4 step heights upstream from the step. A heat flux sensor port (1/2-20) is 2.85 step heights downstream from the step. Fuel injection ports are located 13.15, 8, and 4.5 step heights upstream of the step. Sapphire view ports are 5.5 and 2.75 step heights upstream of the step. The igniter is 1 step height upstream, and there are quartz optical access and PIV windows the same as the original test section.

This test section also incorporates an air forcing slot less than 1 step height upstream from the step (Figure 2.8).

![Figure 2.8 - Air Forcing Slot Schematic](image)

Air is delivered to a plenum located beneath the step.

The slot is 2mm wide, machined in an aluminum plenum / plug. The plenum / plug can easily be removed and modified to incorporate different slot configurations, including different angles, and eventually microjets.
2.1.8 Exhaust Section

The exhaust section is 62 centimeters long (Figure 2.9). It connects the test section to the exhaust tube. There are three ports (M14x1.25) for pressure sensors located 17.65, 27.65, and 35.3 step heights downstream from the step. The last port on this section is for a temperature probe (#10-32 straight thread) located 45 step heights downstream from the step.

The exhaust is suddenly expanded to an 8 inch flexible smooth-bore interlocked stainless steel exhaust duct. This is to approximate an “open” condition for the acoustic mode shape. The expansion ratio is approximately 1 to 5. The exhaust gases are blown through the hose to an exhaust trench that runs throughout the entire lab. There is a slight negative pressure in the trench as a large fan circulates the exhaust from all the test cells in the lab.
2.1.9 Fuel Delivery System

The fuel, propane $\text{C}_3\text{H}_8$, comes from a pressurized tank at approximately 100 psi. This fuel flows through a standard duty two-stage pressure regulator to reduce the pressure to 50 psi. Immediately after the regulator is a high gas flow flashback arrester for safety, to prevent the flame from flashing back into the tank. This event is unlikely to occur from the combustor itself, due to the extremely long pipeline that the flame would have to pass through. The regulator and the flame arrester both terminate in $9/16''$-$18$ left hand threads. An adapter is necessary to attach standard $1/4$-NPT right hand pipe lines to this type of thread. This is connected to a ball valve and then a tee, where nitrogen from the nitrogen tank (the same one used to actuate the air valve) meets the fuel line. When the experiment is over, the fuel lines are purged with nitrogen to remove any combustion hazard. The nitrogen purge line is turned off during the experiment, and only fuel runs in the line. Care must be taken to shut off the nitrogen, because the propane is higher pressure than the nitrogen supply, and would escape through the nitrogen line to the air valve.

A flexible braided stainless steel hose assembly (1/4-NPT) connects the tee to a solenoid valve which is used as an emergency shutoff valve. The valve has 3/8-NPT ports, so a bushing is required to accept 1/4-NPT lines. This is an ASCO Red-Hat II 8210G74/AC normally-closed explosion-proof brass 2-way solenoid valve. This valve is UL approved as a safety shutoff device. This valve opens when standard 120 volt, 60 Hz power is supplied. This is wired to an emergency shutoff electrical switch located near the door of the test cell. It is wired in parallel with the warning light above the door of the test cell,
so the red light indicates that the fuel solenoid valve is open. This valve has a maximum differential pressure of 50 psi.

After the solenoid valve, the fuel line changes to 3/8” (outer diameter) stainless steel straight tubing. This is followed by a pressure gauge, then a Swagelok ball valve, and finally a stainless steel Swagelok in-line filter with 60μm pore size. Also available is a 1 gallon receiver tank for the fuel, to take out supply line mass flow limitations. This is usually connected after the meters, but before the solenoid valve, to reduce pressure losses through the other devices. However, when the fuel line is set up this way, the fuel mass flow meter does not read accurately because of the capacitance in the tank. Therefore, the tank should only be used after the steady state (and transient, for ignition) mass flow characteristics are well established.

After the filter, the fuel flows through a Sierra instruments mass flow meter, described in the Sensors section. The main fuel line goes to another tee, where it is divided into two parallel streams to the Moog valve mounting manifold via ¼-NPT stainless steel flexible tubing. The arrangement of the Moog valve uses a spool with 4 ports. This essentially means that the Moog is two valves in one. Both sides of the valve are in phase with each other. This is described in more detail in the Actuators section.

Both controlled fuel lines then go back out the manifold via ¼-NPT flexible stainless steel braided hose assemblies, which is reduced to ¼” (outer diameter) straight steel pipe. This is followed by a metering valve, and finally is attached to the fuel rod, which goes
all the way through the combustor in the cross stream to the other side, where the other
controlled fuel line is attached. The fuel rod is fed from both ends by the Moog valve.
(This effectively doubles the flow rate from the previous setup which involved only one
side of the 2x2 function valve.)

Fuel injection was initially done through a single ¼-NPT port in the top of the combustor.
This was relatively easy to light because the fuel was injected directly downstream from
the igniter, which resulted in a slightly rich mixture for ignition. However, it seemed that
the mixture was not well mixed at the burning zone, and since one goal was to
approximate a 2D flow, a new fuel injection scheme was developed to provide better
cross-stream uniformity. The new injector was a ¼”OD steel tube that went all the way
across the combustor, which could be fed from one or both ends. The tube was perforated
with 80 holes about 0.7 millimeters in diameter. The holes were arranged in 10 rows of
eight holes each at 36° intervals. This created good cross-stream uniformity, but later it
was discovered that this arrangement decreased the authority of the control action. It
appears that the holes that are oriented upstream (counter-flow) create a jet into the
oncoming air stream. The jet breaks down into vortices where mixing is quite high. The
result is that the fuel is mixed in the streamwise direction, which is undesirable for
control because it has the effect of smearing out the spatial variation of the control fuel.
A second injector was designed that had one row of 10 holes about 2mm in diameter.
This fuel rod can be oriented at any angle by locking the compression fitting at the
desired angle (Figure 2.10).
The authority was then tested at different angles to test the theory that counter-flow injection reduced authority. The authority was tested by sending a sinusoidal signal to the Moog valve, and evaluating the equivalence ratio laser sensor for different injector angles (without burning, to clearly see the effect of actuation, not the effect of instability). Good authority resulted in a high amplitude modulation of the equivalence ratio. This occurred when the injector holes were oriented downstream (0° co-flow). The worst response was when the injector holes were oriented upstream (counter-flow). This resulted in an equivalence ratio fluctuation of almost zero amplitude. +90° and -90° were also tested. These orientations resulted in equivalence ratio fluctuation between the co- and counter-flow cases (Figure 2.11).
This suggested that the best orientation for the fuel injector was co-flow. However, it was later determined that this orientation results in greater thermoacoustic instability because the injector holes on the downstream side are more exposed to the velocity fluctuations than the holes on the upstream side. This was tested at different injector angles, in a burning situation. As expected, the counter-flow orientation resulted in lower instability. (For example, the pilot fuel, which was normally kept on at ~10% of the main fuel line to keep the flame lit, was reduced to zero while the combustor stayed stable.) The co-flow orientation resulted in large pressure fluctuations that required some amount of pilot fuel just to keep from blowing out. Therefore, the tradeoff appears to be greater authority for enhanced stability. Since the stability can also be enhanced by supplying a small amount of pilot fuel, the decision was made to maximize the authority and keep the injectors oriented in the co-flow configuration. It seems that the authority of the fuel is the main limiting factor for successful control using fuel modulation.
The igniter consists of a boron nitride plug into which two ceramic igniter leads are inserted. Boron nitride is used because it exhibits extremely high electrical resistivity ($10^8 - 10^{13}$ ohm-cm), but also a high temperature tolerance, up to 2500°C. It is also chemically inert to a wide range of reagents over a large temperature range. The resistivity encourages the spark to jump through the fuel-air mixture between the two terminals rather than jump to the combustor housing. A cover holds the igniter leads in place, and two O-rings are used to seal the top and bottom of the igniter so that there is no fuel path from the interior of the combustor through the plug to the outside. The igniter leads are from a standard grill igniter. These are attached to the terminals of a spark igniter unit, powered by AA batteries. The device contains a DC voltage transformer to boost the voltage. Care must be taken when operating the igniter because it is meant to be mounted, but it is typically used as a handheld device. It should be held with the hand far away from the terminals because the spark is more likely to jump to the hand if it is too close.

All the main combustor sections are connected with a gasket in between the flanges. Initially, a high temperature sheet gasket material was used, specifically 1) alumina-silica fiber, good to 2300°F (1260°C), and 2) alumina fiber good to 3000°F (1649°C). The melting point of stainless steel is about 1400°C. However, this material did not have good cohesion, so it was extremely difficult to cut it or install it without destroying it. Also, after it was compressed for some time (while it was in service for example), it turned into a powdery substance that could not be reused. It was decided to use a lower
temperature material to use as a gasket because the temperature of the combustor did not exceed 230°C during a typical test. Vermiculite coated stainless steel sheet gasketing (1/32” thick) was selected, with a maximum temperature of 1475°F (802°C). This material can be cut with a good pair of scissors or a chisel. The stainless steel inner core keeps the gasket in one shape, so it is much easier to install and reuse.

2.2 Sensors

2.2.1 Mass Flow Meters

The air mass flow meter is a Sierra Instruments 780S-NAA-N5-EN2-P2-V3-DD-0 Flat-Trak. The maximum flow rate is 284 scfm. The maximum pressure is 120 psig. The unit is powered by a 18-30VDC power supply, and it outputs a signal from 0-10VDC which is proportional to the mass flow rate of the air. The meter is accurate to within ±2% of the reading from 10 to 100% of its range. In our case that is generally within 0.6 scfm. The response time is reported as “one second to 63% of final velocity value.” This meter measures the mass flow rate by adding heat to the flow from two streamwise coils (Figure 2.12). The downstream coil is at a higher temperature than the upstream coil, due to the heat added to the fluid. The temperature difference (as measured using a bridge circuit) is inversely proportional to the mass flow rate.
Streamwise temperature difference is inversely proportional to the mass flow rate.

The units are displayed in scfm (standard cubic feet per minute). While the units are clearly a volume flow rate, standard cubic feet per minute is thought of as a mass flow rate because it is directly proportional to mass flow using a standard density. In this case, for air the standard density is \( \rho_s = 1.293 \frac{\text{kg}}{\text{m}^3} \). This formula allows one to find mass flow rate in kilograms per second.

\[
\dot{m} = \text{scfm} \times \frac{1 \text{m}^3}{35.31467 \text{ft}^3} \times \rho_s \times \frac{\text{min}}{60 \text{s}}
\]

Therefore, the maximum air mass flow rate that this device can measure is 0.173 kilograms per second, or 173 grams per second, well above the 67.6 grams per second maximum combustor design.

The fuel mass flow meter is a Sierra Instruments 820-S-H-3-OV1-PV1-V1-MP-300slpm Top-Trak mass flow meter. This device measures flow rate using the same technology as the Sierra 780S Flat-Trak air mass flow meter. This model handles a high flow rate up to
300 standard liters per minute (a mass flow rate as defined above). The meter is powered by a 12-15 volt power supply and outputs a signal between 0-5VDC which is proportional to mass flow rate. The display units are in standard liters per minute (slpm). As before, this can be converted to a mass flow rate using a reference density, in this case

\[ \rho_s = 1.967 \frac{kg}{m^3}. \]

To convert from slpm to kg/s:

\[ m = slpm \times \frac{1m^3}{1000L} \times \frac{\min}{60s} \]

Therefore, the maximum flow rate that this can measure is 0.009835 kg/s, or 9.835 grams per second, well above the 2.17 grams per second combustor design.

### 2.2.2 Linear Photodiode Array

CH* chemiluminescence is measured spatially and temporally using a new sensor design involving a linear photodiode array. An NMOS linear image sensor (S3901-128Q) is available from Hamamatsu Photonics that provides 128 individual photodiodes in a linear array (Figure 2.13). This sensor has good UV sensitivity, which is important because CH emission is around 430nm. Each pixel is 2.5 mm high and 45 μm wide. A flame image can be projected onto this array using the appropriate optics, and a “linear snapshot” can be taken. This has an advantage over a single photodiode, because it provides spatial information. It also has an advantage over a CCD camera, because the data can more easily be streamed to a computer for analysis, and the amount of data can be handled in real-time for control purposes. Each pixel integrates the light intensity over time, and resets when it is read. There is a linear relationship between exposure (lx·s) and output.
The driving circuit reads in the charge and outputs a voltage proportional to the light intensity.

![Image](image)

**Figure 2.13 – Hamamatsu Linear Photodiode Array**

Dimension "a" is 50 μm. Dimension "b" is 45 μm.

The chemical heat release rate can be determined from the consumption of fuel and the enthalpy of combustion.

\[
\dot{Q}_{\text{chem}} = \Delta h_{r,f}^{\circ} w_f
\]

where \(\dot{Q}_{\text{chem}}\) is the chemical heat release rate, \(\Delta h_{r,f}^{\circ}\) is the low heating value for the fuel, and \(w_f\) is the mass rate of fuel consumption. Therefore, by determining the mass rate of fuel consumption, it should be possible to determine heat release rate.
One promising method for determining the fuel consumption using chemiluminescence was proposed by Diederichsen and Gould in 1964\textsuperscript{34}. They determined that “the square root of the power radiated from unit area of flame is a linear function of the mass burning rate per unit area of flame.” This was later refined to focus on the chemiluminescence of short lived radicals like CH and OH, because these radicals are more closely associated with the location of the flame, as opposed to other species like CO\textsubscript{2}, that persist after the reaction zone, but continue to luminesce. If one considers a sheet-like flame, with CH residing only within the sheet, one could consider the amount of CH to be a measure of flame surface area, which can be related to the reaction rate. Higgins et al. used experimental data and linear regression to determine the relationship between the chemiluminescence of the CH radical and the mass fuel consumption in a laminar methane-air flame\textsuperscript{35}.

$$h\nu_{CH} \propto \dot{m} \Phi^{2.72} P^{-0.64}$$

where $h\nu_{CH}$ is the energy of the photons emitted by CH as its temperature changes, $\dot{m}$ is the mass consumption of fuel ($w_f$), $\Phi$ is the equivalence ratio, and $P$ is the pressure. Zinn et al measured CH* chemiluminescence, pressure, and velocity simultaneously in a premixed gas turbine combustor to explain the limit cycle behavior in these systems\textsuperscript{36}.


In the experiment, the flame image passes through an optical bandpass filter centered at 430 nm, the wavelength of CH* chemiluminescence (Figure 2.14). Unlike most CCD arrays which have peak sensitivity in the infrared region, the linear photodiode array has a high UV sensitivity, making it suitable for this application. A bi-convex UV fused silica lens is used to focus the image of the flame onto the chip. The aspect ratio of the flame image is approximately the same as the array itself. The photodiode array has high spatial resolution in the streamwise direction, and integrates the light intensity in the vertical direction. The image domain on the backward-facing step combustor is illustrated in Figure 2.15.

Figure 2.14 – Linear Photodiode Array Sensor Schematic
The flame image is filtered for CH* chemiluminescence and focused onto the linear photodiode array.
2.2.3 Equivalence Ratio Sensor

The equivalence ratio sensor uses a laser and a photodetector. The laser emits a beam of light of the wavelength (3.39 μm) that is absorbed by hydrocarbons like methane and propane\textsuperscript{37}. On the other side of the combustor, a detector is installed that is sensitive to that wavelength of light. When fuel passes through the laser beam, it absorbs some of the laser light and the detector signal is reduced. The intensity of the light can be related to fuel concentration using the Beer-Lambert law, as described by Lee et al\textsuperscript{38}.

$$\frac{I}{I_0} = 10^{-\frac{L_{\text{abs}}}{l}}$$


where $I$ is the intensity of incident monochromatic light, $I_0$ is the intensity of transmitted light through the absorbing species, $\varepsilon$ is the decadic molar absorption coefficient $\left( \frac{cm^2}{mol} \right)$, $l$ is the absorption path length, and $c$ is the concentration of absorbing species $\left( \frac{mol}{cm^3} \right)$.

In the original design, the laser beam passed through the long cross stream direction, which is 16 cm wide (Figure 2.16). This resulted in the laser light being almost completely absorbed because of the long path length. It was therefore impossible to get the rich equivalence ratio fluctuation, because the detector voltage dropped to zero for that part of the signal (Figure 2.17).

![Figure 2.16 - Original Equivalence Ratio Sensor Setup](image)

The path length was so long that most of the signal was attenuated.
The lean measurement is good, but the rich measurement is lost because the laser light is completely absorbed.

The redesigned setup sends the laser beam vertically through the combustor, so that the laser beam only travels through 2 cm of fuel/air mixture (Figure 2.18). This relies on the assumption that the equivalence ratio is uniform in the cross stream direction. Since there is less fuel in the laser beam path, the laser light is not completely absorbed, even during the rich fluctuations, so we can obtain the real equivalence ratio signal (Figure 2.19).
2.2.4 Pressure Sensors

Kistler pressure sensors are used to measure the dynamic pressure response from the interior of the combustor. The 6061B ThermoCOMP Quartz Pressure Sensor (Figure
2.20) can measure 0-2.5 bar up to 0-250 bar. It is water-cooled and designed especially for small combustion engines and for thermodynamic investigations in the laboratory.

![Figure 2.20 - Kistler 6061B ThermoCOMP Quartz Pressure Sensor](image)
This pressure sensor is water cooled to maintain internal temperature.

### 2.3 Actuators

#### 2.3.1 Air Valve

Control actuation is accomplished using a Dynamco D1B2204 Dash 1 direct solenoid poppet air valve (Figure 2.21). This valve can supply 3.0 slpm of air when supplied with 100psig. The valve is connected to a plenum beneath a 2 millimeter spanwise slot less than 1 step height upstream of the step.
The transfer function for this valve was determined from the step response using 5 volts (TTL) as the input and a hot-wire anemometer as the output. The hot-wire bridge voltage is calibrated with a mass flow rate. The transfer function can be represented by a first order system with a 6 millisecond delay.

\[
G_c(s) = \frac{\dot{m}(s)}{u(s)} = \frac{0.04534}{s + 142.9} e^{-0.006s}
\]

where \(\dot{m}\) is mass flow rate (kg/s) and \(u\) is the input to the valve (V). The Bode plot in Figure 2.22 indicates the break frequency at 23 Hz.
2.3.2 Fuel Valve

Another valve used for actuation is the Moog D633-7315 AIC Direct Drive Valve (DDV) (Figure 2.23). It has its own built in feedback loop to ensure the spool position using an LVDT. This feedback loop is controlled by the Moog D143-098-013 Single Axis Electronic Controller. This unit is powered by a 48V Condor Power Supply, which also powers the valve. The controller accepts inputs from -10 VDC to 10 VDC. This is proportional to desired spool position, although it was found that the mechanical spool limits are such that a signal of -5 volts corresponds to maximum open, while +5 volts corresponds to minimum open.
A transfer function for this valve was determined using system identification. White noise with a bandwidth of 1000 Hz was the input. The spool position, measured with the LVDT was the output. The spool position is related to mass flow rate by a calibration.

The transfer function is

\[
G_c(s) = \frac{\dot{m}(s)}{u(s)} = \frac{0.03837s^3 - 69.11s^2 + 1.786 \times 10^5s + 1.495 \times 10^8}{s^4 + 2634s^3 + 7.934 \times 10^6s^2 + 1.034 \times 10^{10}s + 3.946 \times 10^{12}}
\]

where \( \dot{m} \) is mass flow rate (kg/s) and \( u \) is the input to the valve (V). The Bode plot in Figure 2.24 indicates resonance between 175 Hz and 191 Hz.
2.3.3 Main Air Valve

There is an electronically controlled valve on the main air line used to set the operating condition. This valve is used in concert with the Sierra air mass flow meter to create a mass flow controller using PI control. This valve consists of a Badgemeter globe valve (1004GCN3cSVOP60P36), a pneumatic actuator (BLRA4), a voltage-pressure transducer (Fairchild TA7800-001), and a pressure regulator (Fairchild 65832). The pressure regulator is attached to a tank of nitrogen via 0.25 inch braided stainless steel flexible tubing, a ball valve, and a nitrogen tank pressure regulator (Air Products E11-215D). Nitrogen is used for convenience, because nitrogen is also used for pressure tests and gas line purging. The pressure is regulated down to about 15 psi. This line has two possible outlets: 1) the pneumatic positioner, and 2) the bleed hole on the electro-pneumatic transducer. The transducer is powered by a 24V power supply (Omron 582H-3324) and accepts a 0-10 volt signal from the computer. At 0 volts, the bleed hole opens all the way,
so there is no pressure on the pneumatic actuator to open the valve. At 10 volts, the bleed hole closes and all the pressure is available to open the valve. The flow rate at the pressure setting (on the main line, not on the control line) of 50 psi produces over 180 scfm air flow rate. Settings between 0 and 10 volts open the valve in a non-linear fashion.
3. Proper Orthogonal Decomposition and RePOD

A new sensor for combustion control was introduced in Chapter 2. The sensor gathers high resolution spatial and temporal data. This chapter describes the technique used to extract the most important features of the data, thereby reducing the data set, and allowing use in online control.

The proper orthogonal decomposition (POD) method is used to batch process data and create a reduced-order model, and has been used for offline calculations. This chapter explains this method, as well as a new technique of determining POD modes recursively (RePOD) so the model can be updated in real time.

3.1 The POD Method

POD is a tool for extracting coherent structures from numerical data, and it is a systematic and optimal way to derive reduced-order models. In POD, one uses numerical results to construct a space of optimal basis functions that describe the different modes of the flow, and apply these functions to construct time-dependent ordinary differential equations (ODEs) that determine the amplitudes of the corresponding modes under different conditions. The eigenvalues and eigenfunctions are obtained from the covariance matrix of the data evaluated at different time steps, while the ODEs are obtained from a Galerkin expansion of the dependent variables in these basis functions, and projecting the original Navier-Stokes equations onto their space.
If \( u(x,t) \) is a zero-mean flow variable, then the POD method seeks to generate an approximation for \( u \) by using separation of variables as

\[
\hat{u}(x,t) = \sum_{i=1}^{l} \alpha_i(t) \phi_i(x)
\]  

(1)

where \( \alpha_i(t) \) is the \( i^{th} \) temporal mode, \( \phi_i(x) \) is the \( i^{th} \) spatial mode, \( l \) is the number of modes chosen, and \( t \) and \( x \) are the temporal and spatial variables, respectively. Also, let \( m \) be the number of temporal points in the flow data ensemble, and \( n \) be the number of spatial points (depending upon the number of sensors). The POD method consists of finding \( \phi_i \) such that the error \( u(x,t) - \hat{u}(x,t) \) is minimized. This optimization can be stated as follows.

Denote \( \{\phi_i(\cdot)\}_{x=x_1,\ldots,x_n} = \phi \in \mathbb{R}^n \). The POD method is the following optimization problem:

\[
\min_{\phi} J_m(\phi_1,\ldots,\phi_l) = \sum_{j=1}^{m} \left\| Y_j - \sum_{k=1}^{l} (Y_j^\top \phi_k) \phi_k \right\|^2
\]  

(2)

subject to: \( \phi_j^\top \phi_j = \delta_{ij}, 1 \leq i,j \leq l, \phi = [\phi_1,\ldots,\phi_l] \)

where \( Y_j \in \mathbb{R}^n \) is the vector of flow data \( u \) at time \( t = t_j \). By definition\(^{39}\), \( \phi \) from Equation 1 is a POD modal set if it is a solution to the optimization problem (2) for any

---

value of \( l < m \). The POD modal set can be obtained using the “method of snapshots”\(^{40,41}\) as given below:

\[
\phi_k(x_i) = \sum_{j=1}^{m} A(j,i)Y(x_i,t_j) \frac{Y(x_k)}{\sigma_j}, \quad i = 1, \ldots, l, \quad k = 1, \ldots, n
\]  

(3)

where \( Y = B\Sigma A^T \), \( A \) and \( B \) are unitary matrices, and

\[
\Sigma = \begin{bmatrix}
\sigma_1 & & \\
& \sigma_2 & \\
& & \ddots \\
& & & \sigma_l
\end{bmatrix}, \quad \sigma_1 \geq \sigma_2 \geq \cdots \geq \sigma_l.
\]

The eigenvalues corresponding to the POD modes are the squares of the singular values \( \{\sigma_1 \geq \sigma_2 \geq \cdots \geq \sigma_l\} \), and represent the energy content of the modes.

### 3.2 The RePOD Algorithm

Since the goal is to be able to determine a recursive procedure that is capable of updating the modes of the system on-line and using very few computations, we address the same optimization problem as in Equation (2), but proceed somewhat differently to determine the solution.

Suppose we begin at time \( t_m \), with \( \phi^{(m)} \), the POD solution to Equation (2) corresponding to the flow data set \([Y_1, \ldots, Y_m]\). Given a new measurement \( Y_{m+1} \) at time \( t_{m+1} \), instead of minimizing \( J_{m+1} \), we seek to minimize \( \Delta J \), defined as

\[\text{references}\]

\(^{40}\) A. Newman, “Model Reduction Via the Karhunen-Loeve Expansion,” Technical Research Report, T. R. 96-32 and 96-33, Institute for Systems Research, University of Maryland, Maryland, USA.


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\[
\text{Min}_{\phi} \Delta J(\phi_1, \ldots, \phi_l) = \left\| Y_{m+1} - \sum_{k=1}^{l} (Y_{m+1}^T \phi_k) \phi_k \right\|^2 \tag{4}
\]

subject to: \( \phi_i^T \phi_j = \delta_{i,j}, \ 1 \leq i, j \leq l, \ \phi = [\phi_1, \ldots, \phi_l] \)

The assumption is that with the addition of the new data set, the number of POD modes does not change.

Equation (4) can be solved as follows:

Step 1: Find \( \phi_{i}^{(m+1)} \) that minimizes \( \Delta J^{(1)} = \left\| Y_{m+1} - (Y_{m+1}^T \phi_i) \phi_i \right\|^2 \) over all \( \phi_i \) under condition that \( \phi_i^T \phi_i = 1 \).

Step \( i \): Using the values of \( \phi_{i}^{(m+1)}, \ldots, \phi_{l}^{(m+1)} \), find \( \phi_{i}^{(m+1)} \) that minimizes the overall \( \phi_i \),

\[
\Delta J^{(i)} = \left\| Y_{m+1} - \sum_{k=1}^{i-1} (Y_{m+1}^T \phi_k^{(m+1)}) \phi_k^{(m+1)} - (Y_{m+1}^T \phi_i) \phi_i \right\|^2.
\]

Normalize \( \phi_{i}^{(m+1)} \). Continue for \( i = 2, \ldots, l \).

The minimization of \( \Delta J^{(i)} \) in Step \( i \) can be carried out using gradient techniques:

\[
\phi_{i}^{(m+1)} = \phi_{i}^{(m)} - s \left. \frac{\partial \Delta J^{(i)}}{\partial \phi_i} \right|_{s>0}
\]

\[
\phi_{i}^{(m+1)} = \phi_{i}^{(m)} + s \left( Y_{m+1} - \left( \sum_{k=1}^{i-1} (Y_{m+1}^T \phi_k^{(m+1)}) \phi_k^{(m+1)} + (Y_{m+1}^T \phi_i^{(m)}) \phi_i^{(m)} \right) \right) (Y_{m+1}^T \phi_i^{(m)}) \tag{5}
\]

Equation 5 is the RePOD algorithm. While this does not guarantee orthogonality of the \( \phi_i^m \) s at each time \( t_m \), it leads to an orthonormal set of modes as \( t \to \infty \). Finally, the
recursive algorithm can be initiated by calculating the POD modes from the first $m$ flow data sets.

In this experiment, the “snapshots” are 128 simultaneous 434 nm light intensity measurements of the combustion zone. The algorithm for extracting POD modes recursively is as follows.

Step 1: Take a linear snapshot ($Q$) of the flame using the linear sensor.

Step 2: Calculate the fluctuation ($Q'$) by removing the mean ($\bar{Q}^m$).

$$Q' = Q - \bar{Q}^m$$

Step 3: Calculate amplitude ($\alpha_1$) of first POD mode ($\phi_1^m$).

$$\alpha_1 = Q' \phi_1^m$$

Step 4: Calculate new POD mode ($\phi_1^{m+1}$) using the POD adaptation gain ($\beta$).

$$\phi_1^{m+1} = \phi_1^m + (Q' - \alpha_1 \phi_1^m) \alpha_1 \beta$$

Step 5: Normalize POD mode.

$$\phi_1^{m+1} = \frac{\phi_1^{m+1}}{\|\phi_1^{m+1}\|}$$

Step 6: Compute new mean using the forgetting factor ($\mu$).

$$\bar{Q}^{m+1} = (1 - \mu) \bar{Q}^m + \mu \cdot Q$$

This algorithm outputs the amplitude of the first POD mode (Step 3) and calculates the POD basis function recursively (Step 4). This allows one to track the most energetic
mode even as the system changes due to control action or other factors. The amplitude of the POD mode can then be used as the basis for a control strategy.

In summary, the POD method is used to create a reduced-order model for use in system identification and controller design, as shown in Chapter 4. RePOD is used to update the model in real time as the controller operates.
4. Adaptive PosiCast Controller

4.1 Background

In this experiment, a model based controller called adaptive PosiCast was used for pressure stabilization. The adaptive PosiCast controller has been developed to stabilize dynamic systems with large time delays by predicting future pressure response to eliminate the delay effects on the closed-loop and using an adaptive algorithm to adjust its parameters\(^42\). The adaptive PosiCast controller was implemented by Riley et al on a swirl stabilized industrial gas turbine scaled rig resulting in a reduction of the primary unstable frequency by up to 20 dB\(^43\). Robustness studies showed that adaptive PosiCast retains control for a 20% change in frequency and a 23% change in air mass flow rate. In addition to the above, Park et al implemented adaptive PosiCast on a liquid-fueled axisymmetric dump combustor, completely stabilizing the pressure at the unstable frequency\(^44\).

4.2 System Identification

A model of the system is needed in order to design an adaptive PosiCast controller. System identification is used to generate a transfer function of the plant, with the form:

---


\[ G_p(s) = \frac{\alpha_i(s)}{u(s)} = G_{p,0}e^{-\tau} \]

where \( \alpha_i \) is the amplitude of the first POD mode, \( u \) is the input to the control valve, \( G_{p,0} \) is a delay free system, and \( \tau \) is the time delay.

**4.3 Implementation**

The adaptive PosiCast controller attempts to predict future outputs using a Smith Controller, and uses a phase lead compensator to drive the future output (parameter fluctuation) to zero (Figure 4.1). The controller implemented is a discrete form, where the Smith Controller is a finite time discrete integration multiplied by a weighting function (discretized as \( \lambda_j \)). The weights \( \lambda_j \) and the gains \( k_1 \) and \( k_2 \) are adaptively updated according to the adaptation law:

\[
\dot{k}(t) = -\text{sign}(k_p)\alpha_i(t)dt(t - \tau), \text{ where } k^T(t) = [-k_1 - k_2 \lambda_n(t) \cdots \lambda_i(t)],
\]

\[
d^T(t) = [\alpha_i(t) u_c(t) u(t-ndt) \cdots u(t-dt)], \text{ and } u_c(t) = \frac{1}{s + z_c}u(t).
\]

\( \lambda_1 \cdots \lambda_n \) are used to eliminate the delay from the closed loop and are determined adaptively. \( n \) is determined by the time delay \( (\tau) \) in the system ID model \( G_p(s) \), \( ndt = \tau \), where \( dt \) is the time step. \( k_1, k_2 \), and \( z_c \) are components of the phase lead compensator

\[
k_1 \frac{z_c}{s + z_c + k_2}, \text{ where } z_c \text{ is selected to stabilize the unstable mode of the delay free system } G_{p,0}, \text{ while } k_1 \text{ and } k_2 \text{ are determined by the adaptation law.}
\]
This controller is implemented on a backward-facing step combustor in Chapter 5, and an axisymmetric dump combustor in Chapter 6.
5. Results (Backward-Facing Step Combustor)

POD-based control using the linear photodiode array and the adaptive PosiCast controller was tested on the backward-facing step combustor described in Chapter 2. The results are presented in this chapter, beginning with a characterization of the uncontrolled combustion dynamics.

5.1 Dynamic Characteristics of the Uncontrolled Combustor

Figure 5.1 shows the stability map of the combustor when burning propane at atmospheric inlet temperature and pressure, presented in terms of the equivalence ratio ($\phi$), and the Reynolds number, $Re = \frac{Uh}{\nu}$, where $U$ is the velocity before the step, $h$ is the step height (20 millimeters), and $\nu$ is the kinematic viscosity. Blow out occurs near $\phi = 0.5$, the flammability limit, and at different operating conditions due to a combination of weak flame anchoring and high ($\frac{u'}{U} \approx 100\%$) velocity fluctuations. Region A contains operating conditions that consistently show overall sound pressure level between 150 dB and 160 dB. Region B shows a wider range of overall sound pressure levels, from 140 dB to 160 dB. Region C was highly unstable, with sound pressure level $> 160$ dB, characterized by high power (60 kW – 80 kW) and periodic flashback and flame extinction. In this set of experiments, the combustor was operated at $\phi = 0.65$ and $Re = 8475$ (Region A, marked with an “X”). The overall sound pressure level of the combustor at this operating condition when uncontrolled is 156 dB. The upstream velocity is 6 m/s. The mass flow rates of air and fuel are 24 g/s and 1 g/s, respectively. The combustor power is 47 kW. Figure 5.2 shows the power spectral
density plot of the pressure signal with a peak at 38 Hz, which corresponds to the quarter-wave acoustic mode of the combustor.

Figure 5.1 – Stability Map
Region A shows consistently unstable behavior. Region B shows a range of sound pressure levels. Region C is highly unstable.

Figure 5.2 – Uncontrolled Power Spectral Density
A CCD camera was used to visualize the relationship between the linear sensor image, and the flame characteristics. Figure 5.3 shows the pressure signal, velocity, and the corresponding frame numbers.

To calculate the upstream velocity from pressure measurements and acoustic analysis, pressure was measured at four different locations (x = 35.5, 80, 128 and 163.5 cm with respect to the inlet. step is at x = 93cm.). Then RMS values at each point are calculated from the measurements and used in the 2D acoustic equation to generate a quarter wave mode whose frequency matched the experimentally observed peak frequency. This mode shape was scaled based on the pressure measurements and differentiated with respect to length to get velocity fluctuations using the momentum relation. All four measurements were in phase. Furthermore, the ¼-wave mode most closely resembled the data compared to the ¾-wave mode. Hence the velocity can be estimated to lag the pressure by 90°, with \( u' \) calculated from the momentum relation. Note that negative velocity occurs in Frames 2-4 and Frames 14-16, resulting in flashback and significant upstream burning.

Frames 1-3 show entrainment of reactants leading the vortex front (dark area leading the vortex). In Frame 4, the two flame fronts collapse such that in Frame 5 the reactants burn and cause a large heat release near the end of the domain. This is followed by peak pressure in Frame 6. Velocity increases until it reaches a peak at Frame 9, and the flame is pushed from the upstream to the downstream until frame 14, where the velocity becomes negative, and the vortex begins to roll up again. The images (Figure 5.4-5.7) are captured at 500 frames per second.
Figure 5.3 – Pressure and Velocity Time Plots
The numbers correspond to the frame numbers in the following images.

Figure 5.4 – A large vortex begins to move.
The linear photodiode image shows a discontinuity at the vortex leading edge.
Figure 5.5 – Burning intensifies away from the step
The linear photodiode captures the high CH\textsuperscript{+} chemiluminescence.

Figure 5.6 – High velocity causes bulk flame motion downstream.
The photodiode image tracks this movement.
Schlieren images were also taken at 500 frames/s. The images are not taken at the same time as the CCD camera / linear photodiode array pictures above, because this equipment blocks the collimated light necessary for Schlieren photography. However, both sets of images are synchronized with their respective pressure signals, with the pressure maximum occurring at Frame 6. Therefore, the frame numbers represent the same stage of the pressure/velocity fluctuation cycle. The pressure signal that corresponds to these images is shown in Figure 5.8. The Schlieren images are Figures 5.9-5.12.
Figure 5.8 – Pressure Signal For Schlieren Images
Note that the pressure maximum occurs at frame 6, so the frame numbers are consistent with the CCD images above.

Figure 5.9 – Increasing Pressure, Decreasing Velocity
A vortex is clearly defined. Flashback occurs in Frames 2-4.
Heat release fluctuations are in phase with pressure, with maximum heat release at Frame 6, as the unburned reactants are caught between merging flame fronts.

The velocity is maximum in Frame 9, pushing the flame in bulk downstream.
5.2 POD Analysis

In order to determine the spatio-temporal characteristics of the combustion dynamics, the data obtained from the uncontrolled combustor was analyzed using Proper Orthogonal Decomposition (POD) methods. Figure 5.13 shows a typical set of POD modes from the linear photodiode array. Figure 5.14 shows the energy associated with each mode shape. The first four modes capture 95% of the energy. Figure 5.15 shows the frequency spectrum of the amplitude of each of these modes. The first pair of modal amplitudes shows a peak at 38 Hz. The next pair shows a peak at the harmonic, 77 Hz. Figure 5.16 shows the average linear sensor image. These images were generated using 500 snapshots, taken at a rate of 500 Hz.
Figure 5.13 – POD Mode Shapes
The first four POD mode shapes are shown.

Figure 5.14 – POD Mode Cumulative Energy
The first four POD modes capture over 95% of the energy.
The first two modes have a time varying amplitude with a peak frequency at 38 Hz. The second two modes have a peak at 77 Hz, corresponding to the ¾ wave mode.

Peak CH* chemiluminescence occurs at pixel #60, which is about 2.2 step heights downstream of the step.

5.3 System Identification and Adaptive PosiCast Controller

System identification is used to determine a transfer function relating $\alpha_1$ and the valve input signal. Band-limited white noise with a bandwidth of 100 Hz was sent to the air
solenoid valve from the dSPACE computer (Figure 5.17). Linear sensor images were stored in the National Instruments computer at 500 frames/sec. The POD method was used to extract the amplitude of the first POD mode.

![Figure 5.17 - System ID Input Output Data](image)

The top signal is band-limited white noise to the fuel injector. The bottom signal is the amplitude of the first POD mode.

A model of the system is needed in order to design an adaptive PosiCast controller. System identification was used to create a model using subspace methods. The system can be represented by the following transfer function

\[
G_p(s) = \frac{\alpha_1(s)}{u(s)} = G_{p,0}e^{-\tau s} = \frac{0.85s + 982.7}{s^2 + 4.358s + 5.346 \times 10^4}e^{-0.0025s}
\]

where \( \alpha_1 \) is the amplitude of the first mode, \( u \) is the input to the control valve, \( G_{p,0} \) is a delay free system, and \( \tau \) is the time delay.

The pole-zero map is shown in Figure 5.18. The system is relative degree 1 with stable zeros, so the adaptive PosiCast controller can be used. In this case, the adaptive PosiCast
controller has the following parameters, determined from the system identification model.

\[ \tau = 2.5ms, \ dt = 2.5ms, \ n=1, \text{ and } z_c = 500. \]

Figure 5.18 - Pole Zero Map of System
The system is relative degree one with stable zero, allowing the use of Adaptive PosiCast.

5.4 Results

The adaptive PosiCast POD-based controller was tested using the air forcing slot as an actuator. The amplitude of the first POD mode is used as the input to the adaptive PosiCast controller. The control schematic is shown in Figure 5.19. The Hamamatsu linear photodiode array sends linear snapshots of the flame to the National Instruments board. The NI board calculates the amplitude of the first POD mode and updates it using the RePOD technique to incorporate changes in the dynamics due to control. The most energetic mode is tracked even as the system changes due to control action. The amplitude is then sent to the PosiCast controller running in the dSPACE board to generate a control signal to the solenoid air forcing valve. The initial and final POD mode

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shapes are shown in Figure 5.20. The forcing mass flow rate (0.79 g/s) is approximately 3% of the total air supply. In Figure 5.21, control is turned on at $t = 1$ sec. The overall sound pressure level is reduced by 6.3 dB (from 156 dB to 149 dB).

Figure 5.20 – Initial and Final Mode Shapes
New mode shape obtained after 4 seconds.
5.5 Additional Results

5.5.1 Comparison of Model-Based Control and Static Air Forcing

It was observed that static air forcing was able to stabilize the system for high mass flow rate. To see the effect of static air forcing with minimum mass flow, air was forced through the slot at a constant mass flow rate, and the corresponding overall sound pressure level reduction was measured for the uncontrolled case when $\phi = 0.65$ and $Re = 8475$. With control, $\phi$ is reduced such that $0.61 < \phi < 0.65$ and $Re$ is increased such that $8475 < Re < 9026$. At high mass flow rates of secondary air (6.5% of the main air supply), static air forcing resulted in pressure reductions up to 10 dB. However, for low flow rates (less than 4% of the main air supply), static air forcing increased the pressure oscillations by as much as 3 dB (Figure 5.22).
5.5.2 Demonstration of Periodic Air Forcing Capability

Periodic spanwise air forcing can greatly reduce pressure fluctuations in even higher instability conditions. In this experiment, the combustor was operated at $\phi = 0.73$ and $Re = 8475$. The overall sound pressure level of the combustor at this operating condition when uncontrolled is 163 dB. The upstream velocity is 6 m/s. The mass flow rates of air and fuel are 24 g/s and 1.1 g/s, respectively. The combustor power is 53 kW. The feedback signal to the air valve was a version of the pressure signal with appropriate gain.

Figure 5.23 shows the time plot of equivalence ratio, control signal, pressure, and $\alpha_1$. Complete stabilization of the unstable frequency is obtained within one second. The overall sound pressure level is reduced by 24 dB. Equivalence ratio fluctuations are greatly reduced, and fluctuations in $\alpha_1$ are also reduced as the burning zone becomes
steady. Figure 5.24 shows the power spectrum, with complete attenuation of the acoustic $\frac{1}{4}$-wave and $\frac{3}{4}$-wave unstable frequency.

**Figure 5.23 – Periodic Air Forcing At Higher Instability Level**

Control is turned on at $t = 1$ sec.

**Figure 5.24 – Power Spectrum**

The 35 Hz quarter-wave mode and the 70 Hz harmonic are attenuated to background noise.
5.5.3 Fuel Forcing

Fuel forcing was also attempted using the Moog valve as feedback with a version of the pressure sensor. The operating condition was $\phi = 0.63$ and $Re = 6264$. The upstream velocity is 4.4 m/s. The mass flow rates of air and fuel are 18 gm/s and 0.73 gm/s, respectively. The combustor power is 34 kW. The setup for the control is shown in Figure 5.25. The feedback to the valve is simply the pressure signal multiplied by a gain. The result is a reduction in pressure oscillations, as shown in Figure 5.26. The overall sound pressure level is reduced by 10 dB (Figure 5.27), while the acoustic quarter-wave frequency is reduced by 15 dB.

![Figure 5.25 - Fuel Forcing Control Schematic](image)

The control signal is the pressure signal multiplied by a gain.
Control to the Moog valve is turned on at $t = 1$ sec.

The peak at the acoustic quarter-wave mode is reduced by 15 dB. The overall sound pressure level is reduced by 10 dB.
6. Results (Axisymmetric Dump Combustor)

POD-based control using the linear photodiode array and the adaptive PosiCast controller was tested on an axisymmetric dump combustor at University of Maryland. The results are presented in this chapter, beginning with a description of the combustor, and a characterization of the uncontrolled combustion dynamics.

6.1 Experimental Setup

POD-based control using the linear photodiode array was also tested on an axisymmetric dump combustor at University of Maryland. The combustor has a square dump configuration 10.2 centimeters high by 14.6 centimeters long (Figure 6.1). The approach to the dump plane is a 4.1 centimeter diameter pipe. At the dump plane, the flow expands into the 10.2 centimeter chamber. The step height is 3 centimeters. Ethylene is premixed with air upstream of the step. Two liquid fuel injectors are located at the dump plane as a secondary fuel stream for actuation, 45 degrees with respect to the flow directions. However, only one fuel injector is used in this experiment. Liquid ethanol is used as the secondary fuel stream. A pressure sensor is located 5.1 centimeters downstream from the dump plane actuator. Measurements on the rig are recorded using a Keithley MetraByte DAS-1801AO data acquisition and control board hosted in a Pentium I PC.
6.2 Dynamic Characteristics of the Uncontrolled Combustor

The baseline condition for this dump combustor is $\phi = 0.7$ and Re = 30,000 (based on step height of 3 centimeters). Gaseous ethylene and air are premixed upstream at 0.9 g/s and 23 g/s respectively. Liquid ethylene is injected using open-loop forcing, with a flow rate of 0.15 g/s. The combustor shows an instability at 40 Hz, corresponding to the acoustic quarter-wave mode. Figure 6.2 shows the pressure signal (degrees with respect to the 40 Hz pressure cycle) of this uncontrolled case. The Schlieren images in Figures 6.3-6.6 indicate large vortices being shed also at 40 Hz. The linear sensor is superimposed on these images, and captures the spatiotemporal CH* chemiluminescence fluctuations.
**Figure 6.2 – Unstable Pressure Signal**

Zero degrees corresponds to the pressure maximum.

**Figure 6.3 – Schlieren and Linear Photodiode Array Images (0°-80°)**

The vortex has been shed from the domain, and the tail is visible.
6.3 POD Analysis

POD analysis was done to generate the POD modes and their amplitudes. The relationship between the amplitude and the control input is then determined using System Identification to generate a transfer function, used to design the controller. 500
consecutive linear array sensor images sampled at 500 Hz were used to generate the POD modes. Figure 6.6 shows the first four mode shapes. Figure 6.7 shows that the first mode contains about 60% of the total energy. Figure 6.8 shows the frequency content of the modal amplitudes. The first three modes contain the unstable acoustic frequency, 40 Hz. The fourth mode contains a harmonic, 80 Hz. The average photodiode image in Figure 6.9 shows that the CH* chemiluminescence reaches its maximum around 50th–60th sensor (8.6-12.7 centimeters downstream from the step; step height = 3.0 centimeters).

![Figure 6.6 - The First Four POD Mode Shapes](image-url)
Figure 6.7 - Cumulative energy in the POD modes
The first mode contains about 60\% of the total energy.

Figure 6.8 - Power Spectral Density of Alpha
The first three modal amplitudes show a peak at 40-41 Hz. The fourth modal amplitude shows a peak at the harmonic, 81 Hz.
6.4 **System Identification and Adaptive PosiCast Controller**

System identification is used to determine a transfer function relating $\alpha$, and the valve input signal. A white noise signal was generated and filtered by a band pass filter with bandwidth of 10 Hz-100 Hz and converted to a binary signal in the Pentium I computer. This signal was then sent to the fuel injector and also used as trigger signal for the linear sensor (Figure 6.10). The pressure signal was stored in the Keithley board with sampling rate of 500 Hz and the linear array sensor signal was saved in the Pentium IV saved at 500 frames/sec.
Figure 6.10 - System ID Input Output Data
The top signal is band-limited white noise to the fuel injector. The bottom signal is the amplitude of the first POD mode.

The transfer function below is obtained using subspace methods$^{45}$.

$$G_p(s) = \frac{\alpha_1(s)}{V(s)} = \frac{G_{p,0}(s)e^{-\tau}}{s^4 + 78.68s^3 + 3.406 \cdot 10^5 s^2 + 1.229 \cdot 10^7 s + 1.707 \cdot 10^9}$$

The pole-zero map is shown in Figure 6.11. The system is relative degree 1 with stable zeros, so the adaptive PosiCast controller can be used. In this case, the adaptive PosiCast controller has the following parameters, determined from the system identification model.

$$\tau = 2ms, \ dt = 2ms, \ n=1, \ and \ z_c = 500.$$

---

6.5 Results

The overall sound pressure level was reduced by 6 dB, and the unstable frequency was reduced to background noise. Figure 6.12 shows the pressure time history. Open-loop forcing at 50 Hz is on until $t = 1$ sec. At $t = 1$ sec, the adaptive PosiCast controller takes over and reduces the overall sound pressure level by 6 dB. The power spectrum is shown in Figure 6.13. The peak at 40 Hz has been reduced to background noise levels. The POD adaptation gain was 0.2. Figure 6.14 shows the POD mode shape initially, and the shape that it adapted to.
Figure 6.12 – Pressure Time History
Open loop forcing from $t=0$ to $t=1$. Closed loop control after $t=1.$

Figure 6.13 – Power Spectrum
Adaptive PosiCast reduces the peak at 40 Hz to background noise levels.
6.6 RePOD Adaptation Gain Analysis

There is an optimal gain for POD adaptation. If the gain is too low, the POD mode does not respond fast enough to reflect changes in system dynamics. If the gain is too high, the POD mode will change continuously, reacting to instantaneous cyclical fluctuations in flame shape, rather than fundamental dynamics. Figure 6.15 shows the POD mode updates when the adaptation gain is 0.1. This gain is too small, so the settling time is large. Figure 6.16 shows POD updates when the gain is 10. This is too high, so the mode shape continues to change even after a steady state operating condition is reached. Figure 6.17 shows the POD updates with the gain set to 1. This gain is appropriate because the settling time is reduced, but the mode shape attains steady state.
Figure 6.15 – POD Adaptation Gain 0.1
The settling time is too large.

Figure 6.16 – POD Adaptation Gain 10
The mode quickly adapts, but then continues to change slightly even though the dynamics remain the same.
The settling time is not too long, and the mode shape attains a steady state.
7. Emissions

7.1 Multiple Performance Goals

Emissions sensors are installed on the rig to provide quantitative measurements of performance characteristics such as NO\textsubscript{x} concentration and burning efficiency. Fuel modulation is a common stabilization technique. The impact of fuel fluctuations on emissions and efficiency has been measured, but the results have not been used in the feedback loop in a way that optimizes several performance parameters simultaneously at a fixed operating condition\textsuperscript{46,47}. Additionally, a study of emissions will provide insight into the possibility that air forcing produces cleaner emissions and more complete burning than fuel modulation. For example, air injection at the step may serve to cool the flame, reducing NO\textsubscript{x}.

Other uses for this equipment will be to correlate the linear photodiode array with emissions characteristics. For example, it appears that the flame becomes more compact when controlled with air injection. Compact flames are associated with low emissions because of decreased residence time in which to form NO\textsubscript{x}. Preliminary analysis of linear sensor images appears to show this compact flame shape after control is applied. If a correlation can be made between emissions and linear sensor image, it is possible that the linear sensor could serve as an inexpensive surrogate for an emissions sensor.


7.2 Setup

Two emissions sensors have been installed in the combustor rig. NO-NO₂-NOₓ, and CO-
CO₂ for emissions and combustion efficiency quantification. The emissions probe is
located 62 centimeters downstream from the step in the exhaust section (Figure 7.1). The
probe extends 20 millimeters (half the combustion chamber height) into the chamber,
through a ½-NPT threaded boss. The probe is attached to a Universal Analyzers Model
270S Stainless Steel Heated Stack Filter. The filter has three three outlets: 1) ¼” Tube
Fitting for calibration gas, 2) 3/8” Blow Back tube fitting (not used), and 3) 3/8” tube
fitting for the sample line (center).

![Figure 7.1 – Probe Location](image)

The sample line is connected to a Universal Analyzers Model 520 Single Channel
Sample Cooler with 3/8-NPT braided stainless steel tubing. The cooler brings the sample
down to 4 °C. A peristaltic pump removes to the exhaust trench the water that is condensed by this operation.

The cooled sample is sent to the “Sample” port of the Thermo Environmental Instruments Model 42C High Level NO-NO₂-NOₓ Analyzer. This device takes in air through a Dri-Rite desicant into the “Dry Air” port. The sample is analyzed and the exhaust from the analysis is removed from the reaction chamber by the dual-head vacuum pump. Some of the sample is diverted pumped out the “Bypass” port, through an accumulator, by the single head bypass pump. The sample is sent to the “In” port on the California Analytical Instruments Model ZRH Infrared CO/CO₂ Gas Analyzer. The exhaust from this is then sent to the exhaust trench. A schematic of this setup is shown in Figure 7.2.

![Figure 7.2 - Emissions Sensor Setup Schematic](image)

The NOₓ and CO/CO₂ analyzers are shown with support equipment.
7.3 NO-NO\textsubscript{2}-NO\textsubscript{x} Analyzer

The Thermo Environmental Instruments Model 42C High Level NO-NO\textsubscript{2}-NO\textsubscript{x} Analyzer uses chemiluminescence to detect NO concentrations. The unit generates ozone from the dried air. This is burned with NO in a below-atmospheric pressure vacuum chamber. A PMT tuned to the wavelength of NO chemiluminescence sends a signal to the electronics, which convert the PMT voltage to NO concentration. To detect NO\textsubscript{2}, the sample is periodically diverted with a solenoid valve to a chamber that converts NO to NO\textsubscript{2}. This is then burned in the reaction chamber, and represents total NO\textsubscript{x}. The difference between NO\textsubscript{x} and NO is the NO\textsubscript{2} measurement. The flow schematic is shown in Figure 7.3.

![Flow schematic of NO-NO\textsubscript{2}-NO\textsubscript{x} Analyzer](image)

Figure 7.3 – NO-NO\textsubscript{2}-NO\textsubscript{x} Analyzer Flow Schematic
Thermo Environmental Instruments Model 42C High Level NO-NO\textsubscript{2}-NO\textsubscript{x} Analyzer

7.4 CO-CO\textsubscript{2} Analyzer

The California Analytical Instruments Model ZRH Infrared CO/CO\textsubscript{2} Gas Analyzer uses infrared light absorptance to determine the concentration of CO and CO\textsubscript{2}. In Figure 7.4,
infrared light emitted from an infrared source (1) is intermitted by a chopper (2) driven by a chopper motor (3) at a certain frequency, then let into a measuring cell (4). The infrared light beam is partially absorbed by the CO in the measuring cell. The unabsorbed portion strikes a detector (5), which is consists of a front chamber and rear chamber, both filled with CO. When the unabsorbed light enters the chamber, the gas absorbs the light and expands. The detector is designed to produce an expansion difference between the front and rear chambers, so a small gas flow is produced and measured by a mass flow sensor (6). The output of the sensor is interpreted by the electronics into concentration.

**Figure 7.4 – CO-CO₂ Analyzer**
California Analytical Instruments Model ZRH Infrared CO/CO₂ Gas Analyzer
8. Conclusions

Proper orthogonal decomposition has been used for the first time for real-time control of combustion instability. This technique is combined with a novel sensor for gathering data quantifying the heat release rate. Model-based control is tested successfully on multiple combustion rigs to verify the control technique, the recursive POD method, and the linear photodiode array.

The new sensor is a linear photodiode array that measures high spatiotemporal resolution CH* chemiluminescence data. This data is processed using the POD method to create a system identification model used to design an adaptive PosiCast controller. During operation, the model is updated recursively in real time using linear photodiode array measurements, and recursive POD (RePOD).

In the backward-facing step combustor using air actuation, a 6 dB reduction in overall sound pressure level is achieved using this control strategy. Furthermore, it is established that adaptive PosiCast control reduces the pressure oscillations when the same flow rate of steady air forcing increases pressure oscillations.

Additionally, the technique is tested on an axisymmetric dump combustor, using a liquid fuel injector as an actuator. The same linear photodiode array is used for feedback, and a 6 dB reduction is obtained over the baseline using adaptive PosiCast POD-based control.