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A Design Methodology for Rapid Implementation of Active Control Systems Across Lean Direct Injection Combustor Platforms

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Abstract

The Virginia Active Combustion Control Group (VACCG) completed the first 9 months of work under the subject NRA Grant NASA Glenn Project (NAG3-2687) in October, 2002. This brief summary is intended to provide a synopsis of the progress that was made during the 2002 fiscal year. It is noted that the research program actually began at Virginia Tech in early December, 2001, due to a delay in the funding. Therefore, the work reported here spans research conducted at the university between January, 2002 and October 15, 2002, not the entire twelve month period of the 2002 fiscal year.

The VACCG team is comprised of engineers at Virginia Tech who specialize in the subject areas of combustion physics, chemical kinetics, dynamics & controls, and signal processing. *Currently, the team's work on this NRA research grant is designed to determine key factors that influence combustion control performance through a blend of theoretical and experimental investigations targeting design and demonstration of active control for five different combustors at university, industry, and government facilities.* To validate the accuracy of our conclusions about control effectiveness, a sequence of experimental verifications on increasingly complex lean, direct-injection combustors is planned. During the first year of effort, work has focused on two different laboratory-scale combustors at Virginia Tech that will allow access for a wide variety of measurements. As the grant work proceeds to future years, one key goal will be to obtain certain knowledge about a particular combustor process using a minimum of sophisticated measurements, due to the practical limitations of measurements on full-scale combustors. In the second year of this grant, results obtained in the first year will be validated on test combustors to be identified in the first quarter of that year. In the third year, it is proposed to validate the results at more realistic pressure and power levels by utilizing the facilities at the Glenn Research Center.

There were numerous accomplishments and results stemming from the completion of their grant's first year of funding. During the work period (1/1/2002 through 10/15/2002), two students were funded full-time on the effort with an additional 0.5 student funded on the cost-sharing budget identified in the contract. The summary report below will provide brief descriptions of the key results for the first-year work tasks identified below.

Introduction

The overall goals of this research grant, as summarized in the proposal are repeated below:

The purpose of this work is to develop a control system design methodology that can be used to rapidly design and deploy an active control system to suppress any existing combustion instabilities on a lean direct injection combustor. To this end, we proposed to do the following:

1. Develop a minimal set of tests to characterize fuel-modulation actuators with regard to their usefulness for active control of combustion.

2. Develop a minimal set of tests for combustors that characterize an existing instability and the impact of fuel modulation.

3. Develop a methodology to determine the size, number and location of actuators to suppress an existing instability from the test data gathered in items 1 and 2.

4. Determine a suitable control structure and adaptive tuning technique that, together with the actuators selected in item 3, will suppress an existing instability.

5. Validate the above items on combustors of increasing complexity.

There were seven work tasks that were offered as part of the three-year work approach that was proposed to reach these five end-goals. Work tasks 1 and 2 were began during the first six months of the grant, with work tasks 3 and 4 being initiated at the beginning of the third quarter of the work period. (Note that the third quarter of the work period began in July, 2002 and ended in September, 2002.) The key work items and corresponding results for the work tasks are presented below, delineated by work task.

Work Task Results

1) Kick-Off Meeting and Investigations

The NRA grant work began in early January, 2002, after funding had been established for two graduate students. At this time, two graduate students, one MS student (Jonathan DeCastro) and one PhD student (Wajid Chishty) began working on actuator and combustor design issues, respectively. A series of phone calls were held with Joe Saus, one of the NASA Glenn technical grant monitors in mid-January timeframe. The overall scope of the grant work plan was discussed and it was deemed appropriate to move forward as discussed in the proposal.

Two other meetings of note were arranged during the first two quarters of the work period. First, Mr. Joe Saus and Dr. Clarence Chang visited the Virginia Tech campus in mid-April, 2002 for two days of meetings with the VACCG faculty and students. During that visit, a tour of the VACCG laboratory was conducted also. The interaction between the NASA Glenn and Virginia Tech engineers, during the April visit, served as the primary kick-off meeting for the program. In addition, the VACCG arranged for one of the graduate students, Mr. Jonathan DeCastro, to visit the NASA Glenn facilities in mid-June. The main purpose for this two-week visit was to help the VACCG research team to become familiar with actuator characterization test-rigs and procedures that the NASA Glenn engineers were conducting on two different actuators scheduled for testing in active combustion control systems. The summer visit allowed a good dissemination of information about the testing issues that were deemed important by NASA engineers.

In early June, an additional MS graduate student (Noah Schiller) was added to the grant team. This addition was in anticipation of the graduation of Jon DeCastro sometime during the Fall 2002 semester. Jon's funding was transferred to the cost sharing budget for the Fall semester; therefore, Noah and Wajid are the two students currently being paid by the NRA funds.

Next, work items completed under the three technical work tasks that were in the timeline for the first twelve months of the grant are discussed.

2) Actuator Performance Characterization Methods

The fundamental goal is to identify parameters that can be associated with the ability of a particular actuator/fuel injection system to control combustion instabilities of a specified sound power level or unsteady heat release rate. The major factors under consideration are actuator bandwidth, modulation percentage and type (proportional or on-off), and atomization characteristics. It is important to distinguish here that the "actuator" in this task refers to both the actuating mechanism, as well as the modulating component of the fuel injection system. Two different actuated fuel injection systems are under study by the VACCG, as part of this task. The first system is a piston-check valve configuration, while the second system is a throttling valve configuration. Both fuel injection system designs rely on a piezoceramic actuation mechanism for the modulation control.

A large amount of work has been completed under this task heading and will be discussed below. However, it is also relevant to note that two of the grant Principle Investigators (W. Saunders and U. Vandsburger) are also managing a senior design project, consisting of fifteen senior students, which is focused on the characteristics and ultimate scaling of the two existing fuel injection system designs. This marks the third year that the PI's have devoted their energies to this type of design class project and the overall benefit to the NASA grant program goals continue to be very positive. For this report, however, only the graduate student work items will be reviewed. If the NASA technical monitors wish to receive documentation about this year's senior design team goals and results, those documents can be provided under separate cover. The fuel injection system characterization work began with the fabrication and testing of all the system components, such as the actuator, the valve, the atomizer, and the other components of the fuel injection system (e.g. accumulator, pumps, etc.). In addition, there has been a significant effort devoted to modeling the unsteady pressures that are expected to exist at the atomizer input location, in anticipation of future correlation with laser measurements of the nozzle (atomizer) sprays exiting under the action of modulation. The key points of this work will be discussed next.

I. Piston and Check Valve System Testing

The first proportional fuel injection system design completed in-house by the VACCG was based on a piston check-valve (Figure 1) operation that produced unsteady pressure pulses used to modulate fuel flow through a simplex atomizer. Certain data have already been reported to NASA about the use of that particular design and will be summarized here only. During open-loop testing, it was determined that this type of design provided approximately 40% pressure modulation and was capable of reducing the lightly damped, noise driven response of an instability in an ethanol combustor by an amount of approximately 5-7 dB. Subsequently, the same fuel injection system was used to implement active control on the first-generation kerosene LDI combustor built at the very beginning of this program. A representative pressure spectrum from that test is shown later in the section discussing unsteady combustor performance characterization.

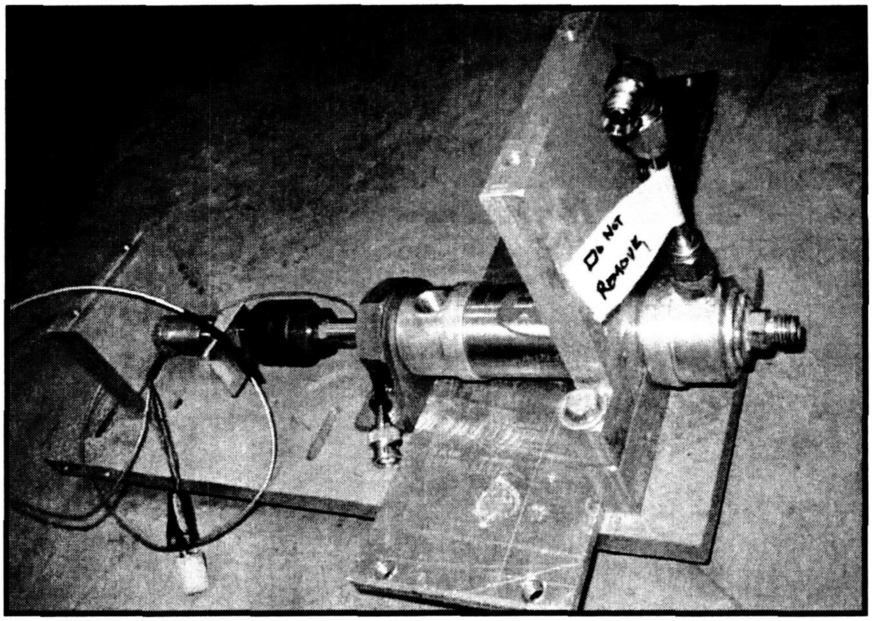

Figure 1: Piston and Check Valve Hardware

II. Throttling Valve System Fabrication and Testing

In order to reduce the piston check-valve scaling requirements on actuator force, a second modulated fuel injection system design was investigated by VACCG members. Within the context of this NRA program, it will certainly be beneficial to rapid implementation of ACC systems if the scaling of the actuator is eliminated as a design variable. The overall system design was completed with the assistance of the 2001-2002 academic year senior design class curriculum. Initial testing of the system showed that an off-the-shelf valve selected for the throttling valve function was not properly designed for compatibility with the extremely small displacements from the piezoceramic stack actuator (on the order of microns of displacement). Therefore, one of the MS student work tasks was to identify a first-generation valve design that would provide the fast opening flow profile needed for this application. The valve was designed, machined, and fabricated completely in-house at Virginia Tech. A photograph of the resulting throttling valve hardware is shown in Figure 2.

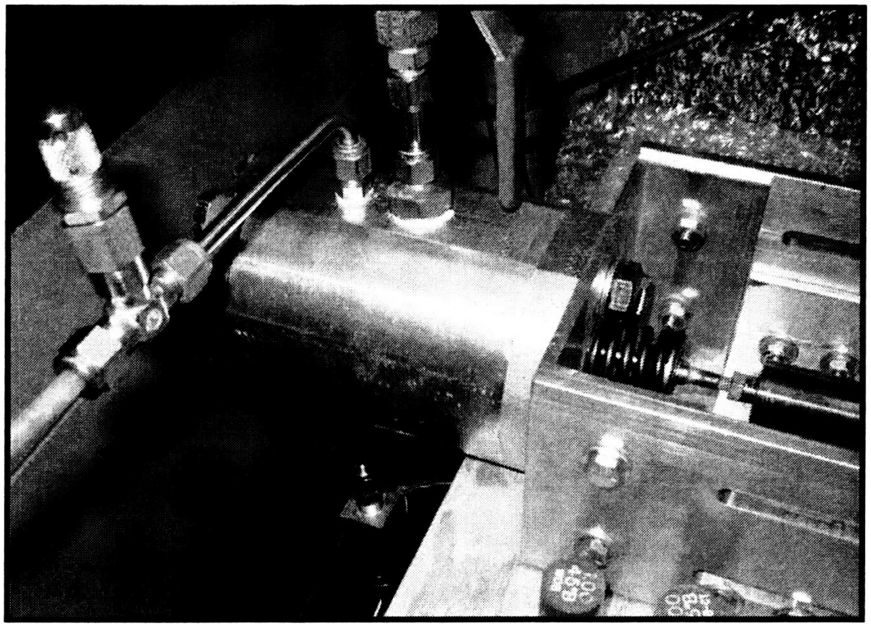

Figure 2: Throttling Valve Hardware

In very recent weeks, we have begun to test the throttling valve with a newly purchased 500 micron piezoceramic stack actuator. The analog amplifier for the stack actuator is currently limiting the actuator bandwidth and output power. A switching amplifier will be tested in coming weeks to determine what bandwidth can be achieved at full modulation power. For now, the present performance of the throttling valve is indicated in Figure 3 below.

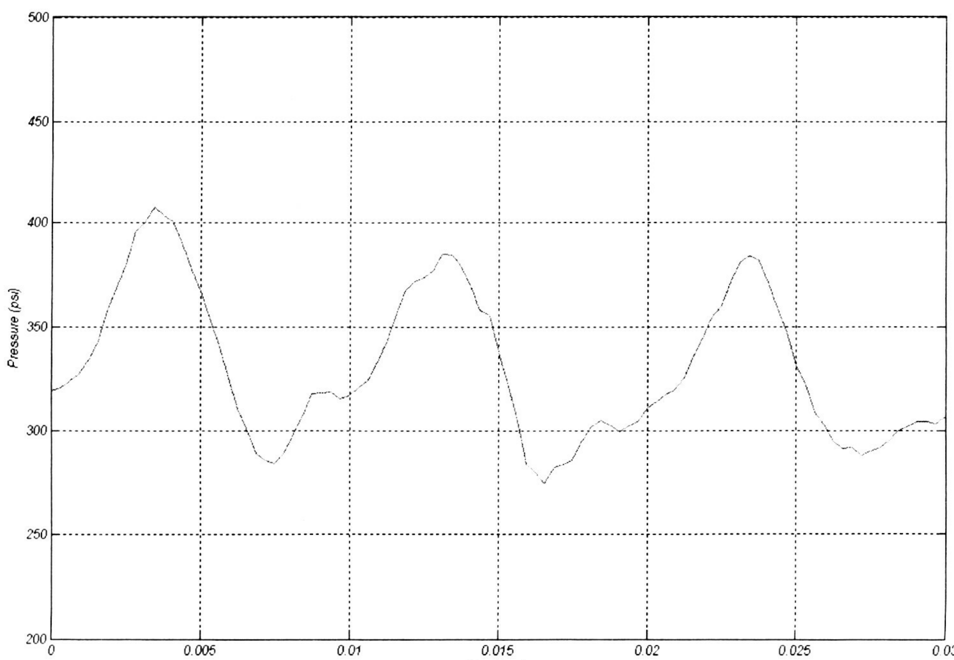

Figure 3: Pressure Modulation Measured at the Atomizer Inlet

The data was obtained with a "bypass" line installed and a mean upstream pressure of 425 psi. The valve was being operated about an offset of 160 um with a swing of $\pm$ 150 um. At this time, the fluctuating pressure amplitude at the nozzle is partially due to a fluctuation in the supply pressure. We are currently working to finalize the performance of the throttling valve system so that active combustion control testing can begin.

III. Fuel Delivery System Acoustic Modeling

One of the fundamental necessities for a rapid ACC implementation scheme is the understanding of the unsteady, modulated flow from the nozzle. To begin addressing this facet of the grant studies, a series of acoustic modeling efforts have been completed. For this report, a brief synopsis will be presented. However, a MS Thesis will be available at the conclusion of this calendar year for any NASA personnel who are interested in all of the modeling details.

Four different models were examined during a systematic investigation that was designed to ensure understanding of increasingly complex acoustic dynamics in the fuel injectors. The first system investigated was a simple closed-tube driven by the piezoceramic-actuated piston (see Figure 1). A comparison of the model and measured SPL values inside the downstream section of the tubing is shown in Figure 4.

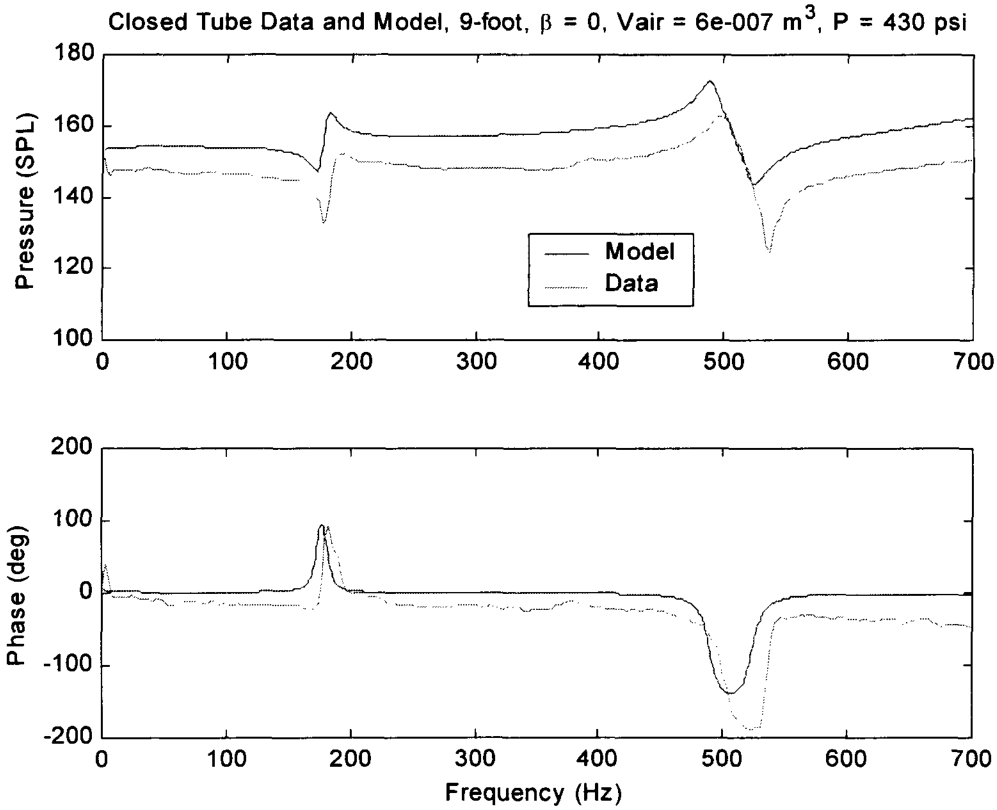

Figure 4: Piston – Closed Boundary Model and Data

As shown in Figure 4, the resonance frequencies of the fuel system piping and piston-stack assembly are predicted quite well. The amplitude is still not as accurate as we wish to predict; however, there are several good hypotheses for this discrepancy and we believe that this will improve as more measurements are acquired for analysis.

The second model also relied on the piston/stack acoustic actuation method but the piping system was terminated with a simplex atomizer. This change provided a straightforward way to assess the types of acoustic impedance that might be attributed to the atomizer hardware. The comparison between model and measured SPL values for this test system, shown in Figure 5, indicates that the atomizer behaves in large part as any junction impedance might behave, i.e. as a small orifice might behave acoustically. Again, the amplitude is not perfectly matched but the frequencies are predicted well.

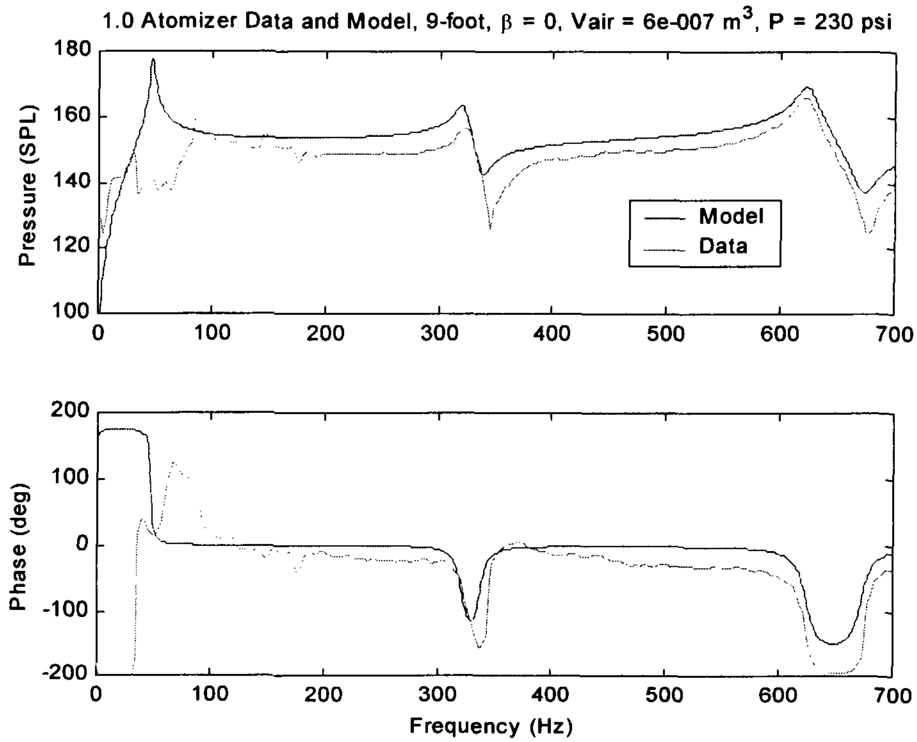

Figure 5: Piston – 1.0 Atomizer Boundary Model and Data

Figure 6 shows the comparison for the third acoustic modeling effort, which utilized the throttling valve as the acoustic source term and a closed pipe boundary condition was repeated for this new actuation method. Again, the resonance frequencies are matched nicely but this time the amplitude is more accurate than before at some frequencies. The differences in amplitude are attributed to a number of factors that will be discussed in the corresponding MS thesis discussion.

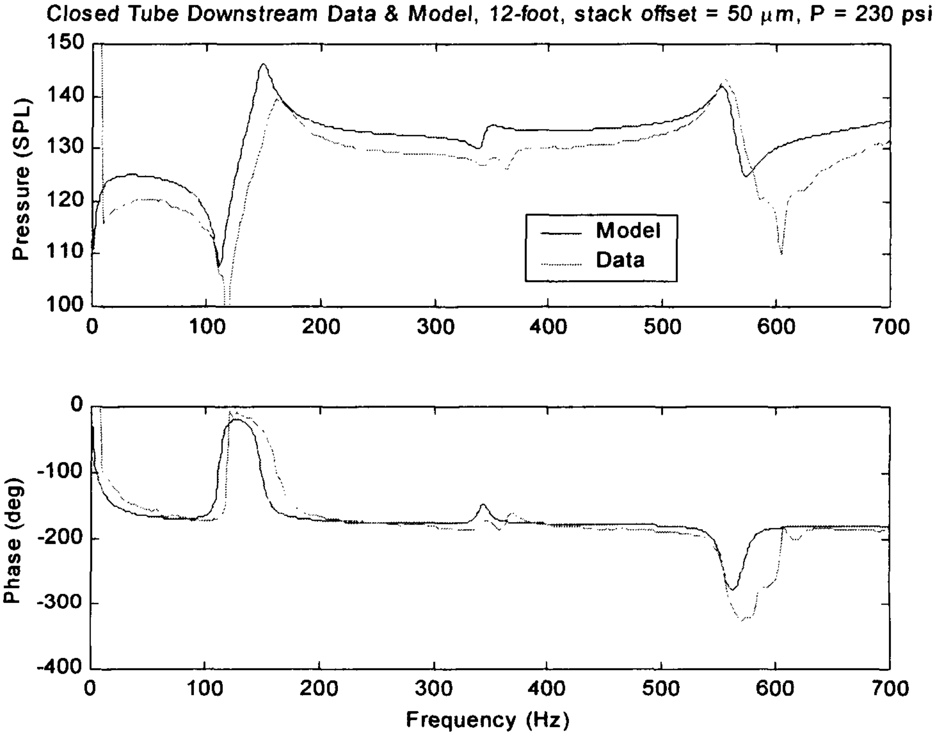

Figure 6: Throttle Valve – Closed Boundary Model and Data

The final acoustic model, currently under investigation, is associated with the throttling valve as the acoustic source and the atomizer end-condition for the piping. One example of this work-in-progress is shown in Figure 7. It is important to recognize several important issues for the acoustic modeling of this system. First, the throttling valve can be operated at a variety of offset positions. This means that the valve head, which serves as the acoustic source, couples the front and rear portions of the piping quite differently as the offset values are changed. In addition, the pressure drop across the atomizer changes with offset position, thereby changing the details of the acoustic impedance that is used to represent the atomizer flow passages. In addition, these changes will also be going on during one complete cycle of the modulated valve position. This means that the acoustic problem is truly nonstationary and thereby precludes precise modeling using the simplified one-dimensional approximations used for the modeling effort so far. Nevertheless, these frequency response functions serve a useful purpose in bounding our expectations about the possible dynamic response that will be expected to play a key role in modulating the atomizer flow sheets for combustion control.

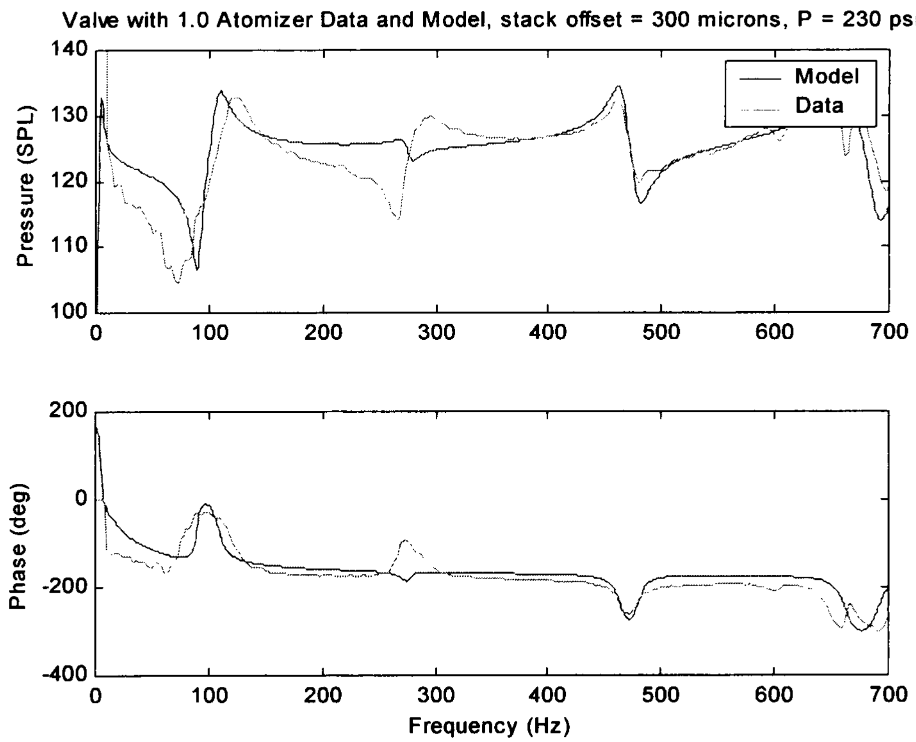

Figure 7: Throttle Valve – Atomizer Boundary Condition Model and Data

IV. There are two other important " characterization" investigations underway for the modulated fuel injection systems. The first study is concerned with quantifying the degradation in fuel spray modulation that results from certain sources of compressibility in the fuel lines that are being modulated. Time constants are being measured for varying inlet pressures in an attempt to create a simplified "linearized" model of the compressibility effects. This information will identify whether the compressibility (caused by solubility of gases in the fuel or air bubbles resulting from other sources such as cavitation or aeration in the fuel tank) is responsible for destroying the bandwidth of the fuel injection systems under any circumstances. In addition, we are attempting to identify certain test procedures that can lead to similar quantitative assessments of compressibility effects on any arbitrary combustor fuel delivery system that must be modulated for active combustion control purposes. The results of this study will be summarized at the end of the Fall 2002 semester and will be made available to NASA at that time.

The final fuel system investigation that should be mentioned is concerned with determining the influence of the atomizer design and flow number on the fuel modulation results. At this time, a PDPA system is being prepared for shipping to Virginia Tech, where it will be used to measure fuel sprays under actuation by the piston or throttling valve injection system. The acoustic modeling and measurements, discussed earlier will be used to guide the fuel spray velocity experiments. The ultimate goal is to develop methods that rely on simplified acoustic models of any fuel delivery system to predict the fuel line pressure at the inlet to the atomizer, and measured behaviors of a particular nozzle design, to quickly assess how the atomizer spray will interact with the combustor generated unsteady pressures encountered by the nozzle sprays.

3) Combustor Characterization Methods

The operating conditions of the combustor determine how a pulse of fuel from an injector will burn both spatially and temporally, and it is the heat release of the burning fuel that ultimately governs control effectiveness. Key issues that determine performance include mixing, the time history of burning due to the flame shape, and the degree of coupling between the heat release and the acoustic mode, which is influenced by the relative positions of the flame and the acoustic mode shape. This task involves the characterization of these dynamic features of the combustor plant. For this case of direct liquid-fuel injection, the dynamic mixing response of the atomization and vaporization must also be determined and will become a critical focus of this work task in coming months.

One of the first requirements under this task was simply the design and fabrication of a liquid-fuel, lean direct injection type of combustor that exhibits a combustion instability (thereby allowing this study to proceed). The current combustor rig is a vertically mounted structure with 150 kW thermal capacity. Photograph of the rig is given in Figure 8.

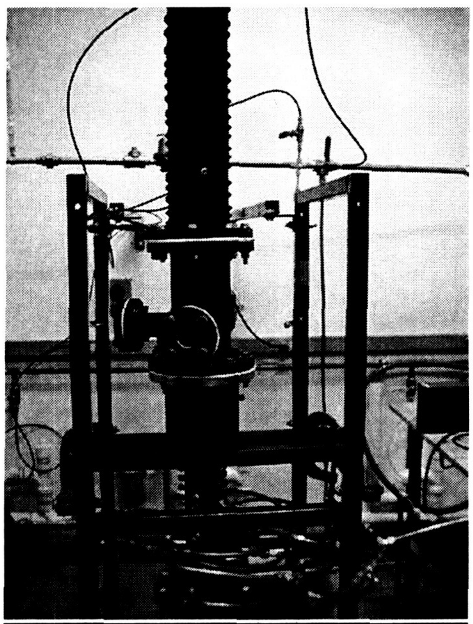

Figure 8: Year-One LDI Combustor Rig

It comprises three main sections, the combustor, the burner and the flow conditioning section, which is connected to the air and fuel supply lines. The combustor is a 5" ID steel cylinder made up of hot and cold sections separated by a ¼" insulation packing made from Fiberfrax gasket paper. The hot section, which also acts as the test section, is 26" long and is equipped with three 90^{o} apart rectangular (8"x3") viewing windows made up of ¼" thick GE Type 124 fused silica quartz plates. The windows have extremely high optical, thermal and physical properties and were provided for complete imaging and laser measurements. The cold section of the combustor has a length of 24" and is wrapped with ¼" copper tubing for water-cooling. The total length of 48" was selected after a series of tests to give the combustor the self-excitation capability.

The burner section consists of an air plenum, a centrally located injection nozzle and an axial swirler, which sits coaxially around the injector. A 2 ½" overlap is provided between the combustor and the burner section so that the complete flame is captured by the viewing windows. The plenum has been fabricated to accommodate various sizes of swirlers and injector nozzles. It is also equipped with two microphone taps for measuring forced velocity perturbations, and two water taps to provide cooling to the face plate on which the combustor sits. The face plate has a diverging quarl and is replaceable. Both pressure atomizing and air assist atomizers can be used. The fuel (and air in case of air assist nozzle) is fed to the injector nozzle from the bottom of the rig through ¼" stainless steel tubing. Axial location of the injector nozzle can be changed by adjusting the position of the lance, which houses the nozzle. A variety of axial swirlers can be used with different vane angles and sizes. Their location can also be changed along the longitudinal axis of the burner.

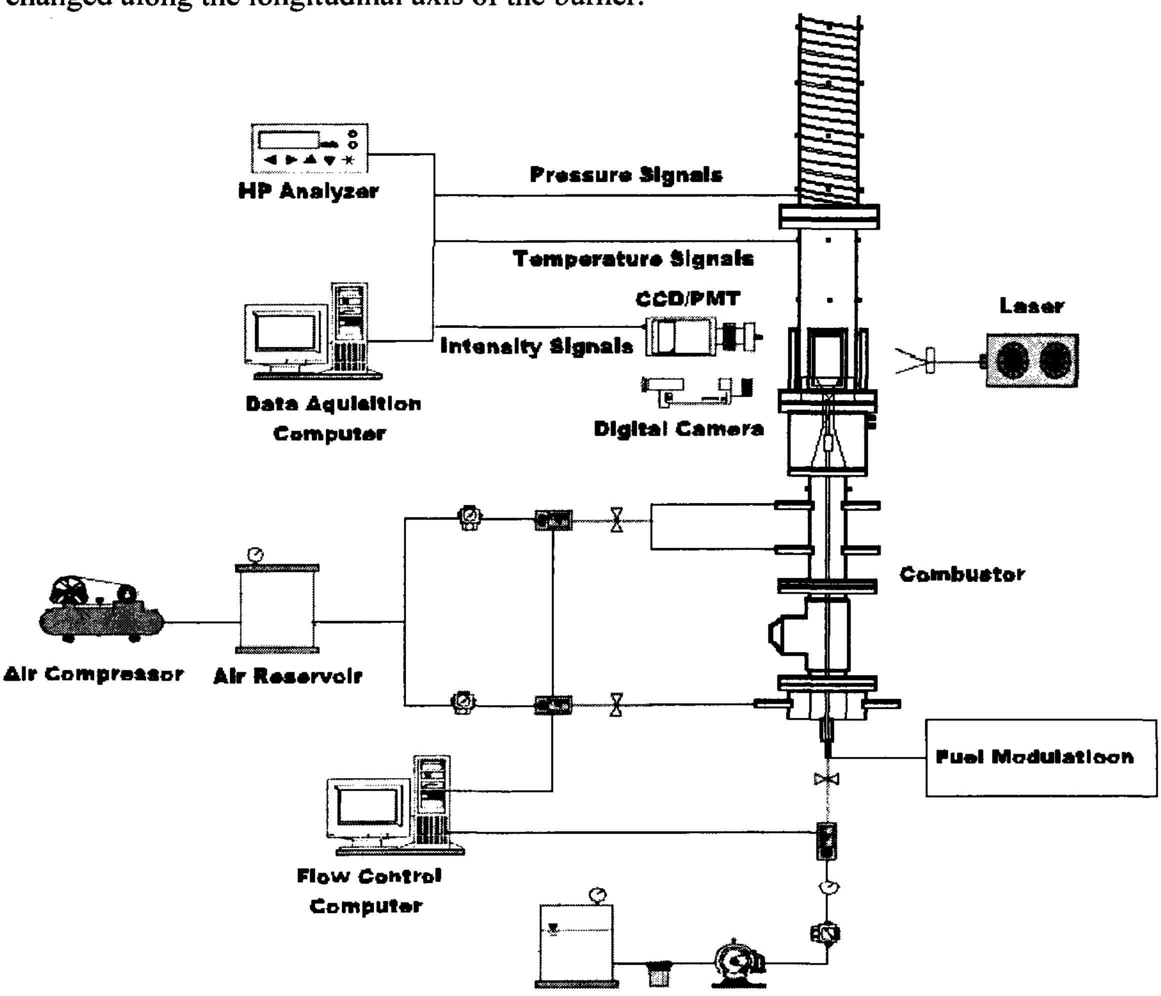

Figure 9: Schematic of Overall Combustor Test Facility

The overall combustion facility layout is shown in Figure 9. Kerosene is used as the combustion fuel and is delivered from the non-pressurized tank to the combustor by a SUNTEC Model 885X gear pump at a maximum pressure of 300 psi. The pump is driven by a ½ hp, 3450 rpm Dayton single-phase electric motor. The fuel feed line comprises: filter, to arrest dust and particle flowing into the feed line; pressure regulator, to maintain a maximum specified feed pressure; accumulator, to avoid pressure pulsation in the feed line; flow control valves, for both coarse and fine metering of the fuel; analog pressure gauges, to monitor feed line pressure at various locations; Flow meter, AWC Model JVA-10KI with HEF-1 sensor, to monitor the fuel volume flow rate; and dynamic pressure transducer, Kistler Model 206, to monitor and record fuel pressure fluctuations in the feed line. The air is fed to the system from a 150 scfm, 125 max psi, Ingersol Rand compressor. Two Eldridge Model 8710 NH flow meters, one each in axial and tangential air supply lines, are provided to monitor air flow to the combustor. Also, pressure regulators and flow control valves are provided to regulate and meter the air flow. The system is also equipped with a rotameter Atheson Model FM 1050B-HA to monitor the air flow to the air assist injector nozzle.

Steady Combustor Characterization

Under this subtask, the burning characteristics of the steady combustors are being mapped for a range of fuel and air flows and for different swirl numbers. The flame characterization will eventually include total chemiluminescence signal (OH)*, distribution of chemiluminescence throughout the flame, and flame area/volume distribution. At this time, measurements of swirl and flame visualization have been completed. Representative data from both measurements are shown in Figure 10 and Figure 11, respectively.

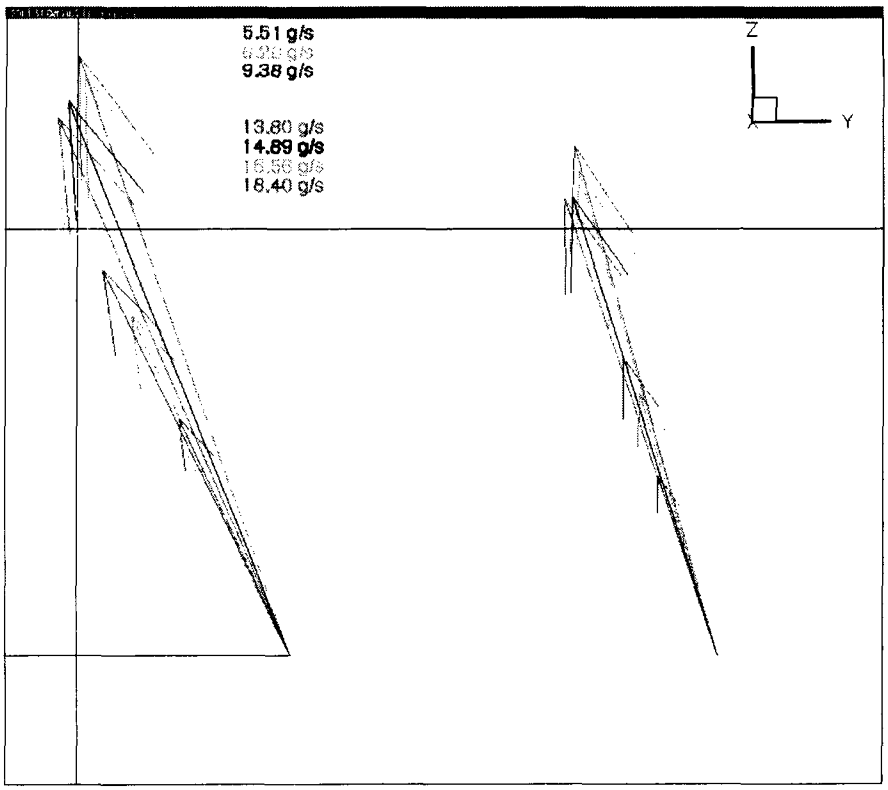

Figure 10: Swirl Flow Vectors

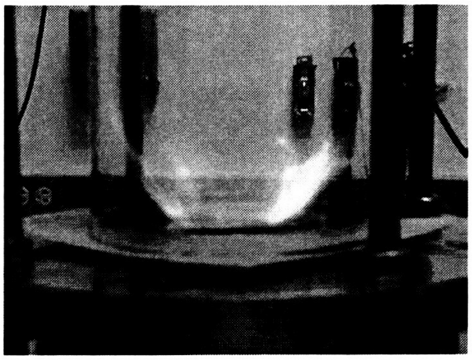

Figure 11: Flame Visualization for LDI Combustor

There was a significant effort in designing and fabricating the new swirl system that led to the compact blue flame shown in Figure 11. Originally, the swirl hardware was not capable of providing this type of flame at any settings. The ability of the flame's heat release rate to couple in to the acoustic dynamics was also improved, as a result. An example of the unsteady pressure power spectra measured inside the combustor chimney is shown in Figure 12. The time domain and frequency domain data both indicate that this combustor is truly unstable, leading to limit cycling response that can be used in the design of ACC systems during the coming months.

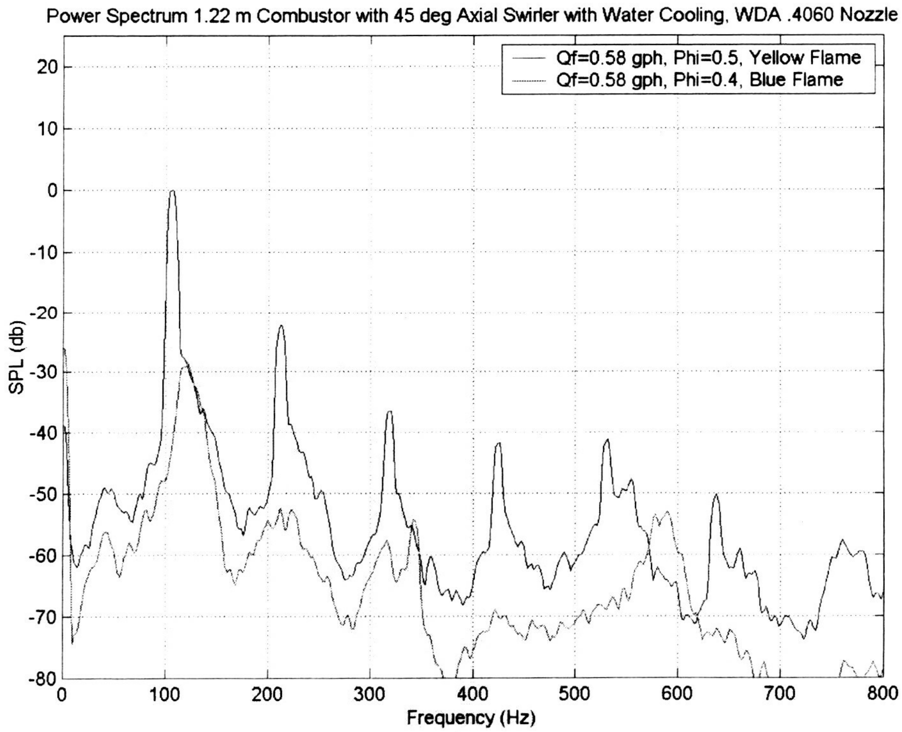

Figure 12: Power Spectrum of LDI Combustor

4) First-Generation Methods for Rapid ACC Implementation

The fundamental objectives of this task build on the results of the previous tasks to determine a methodology for the rapid design and implementation of a control system capable of stabilizing an existing thermoacoustic instability without a large amount of extensive trial and error that characterizes current practice. The design process will attempt to use an energy viewpoint to determine the number, size and location of actuators necessary to stabilize the combustion system. The following discussion represents the initial energy-based design concepts that have been explored during the first nine months of the NRA grant.

Analysis

In its simplest form, a one-dimensional acoustic system excited by heat release is governed by the equation

$$\frac{\partial^2 p'}{\partial t^2} - c^2 \frac{\partial^2 p'}{\partial x^2} = (\gamma - 1)\dot{Q}'\delta(x - x_f)$$

We can always expand the unforced wave equation into a series of normal modes as

$$p' = \sum_i \eta_i(t)\psi_i(x)$$

which results in the uncoupled equations

$$\ddot{\eta}_i(t) + \omega_i^2 \eta_i(t) = \frac{\gamma - 1}{E_i}\dot{Q}'(t)\psi_i(x_f)$$

where $E_i = \int_0^L \psi_i^2(x)\,dx$ and $\omega_i^2 = c^2 k_i^2$. If we are worried about a specific instability which only excites one mode significantly, we can consider a simple model of the thermoacoustic system shown in Figure 13.

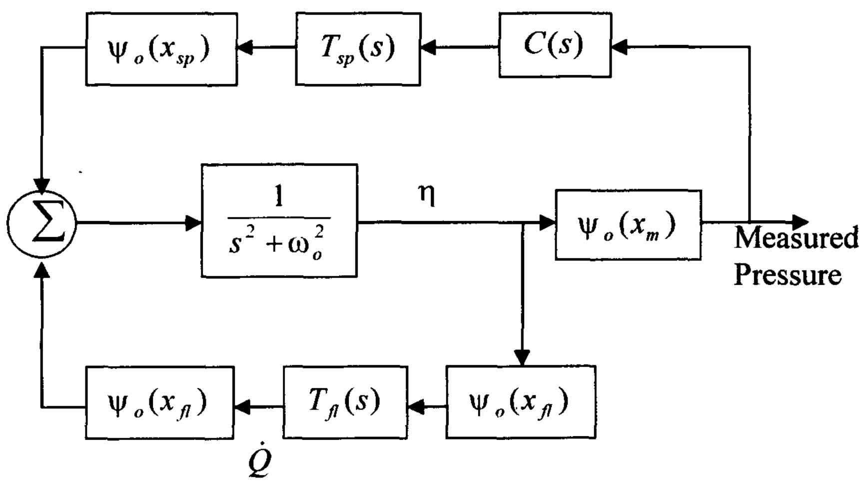

Figure 13: Simplified Thermoacoustic Model with Control

This figure explicitly shows the modal influence coefficients for the pressure measurement location, $\psi(x_m)$, the flame location, $\psi(x_{fl})$, and the speaker input position, $\psi(x_{sp})$. Since in general we will not know the value of these constants, we will lump them together with the unknown transfer functions so that $\psi_o(x_m)\psi_o(x_{sp})T_{sp}(s) \rightarrow T_{sp}(s)$ and $\psi_o(x_{fl})T_{fl}(s)\psi_o(x_{fl}) \rightarrow T_{fl}(s)$. The modal influence coefficients do not need to be identified separately.

We will make the fundamental assumption that near the instability frequency, the flame and speaker transfer functions vary slowly and so may be considered constant in amplitude and phase. This is in contrast to the acoustic transfer function, which varies rapidly in both amplitude and phase at ω_o and hence will induce rapid variations in the closed loop system near the instability frequency.

Because of instability or lightly-damped, closed-loop acoustics, the response of η will be predominantly sinusoidal at the frequency of oscillation, $\eta(t) = A(t)\sin(\omega_{osc}t)$, and hence $\dot{\eta}(t) = \omega A(t)\cos(\omega_{osc}t)$. Thus, the forcing effect of the flame can be written as

$$\begin{aligned} F_{fl} &= |T_{fl}(j\omega_{osc})|\, A(t)\sin(\omega_{osc}t + \angle T_{fl}(j\omega_{osc})) \\ &= |T_{fl}(j\omega_{osc})|\, A(t)\left\{\cos(\angle T_{fl}(j\omega_{osc}))\sin(\omega_{osc}t) + \sin(\angle T_{fl}(j\omega_{osc}))\cos(\omega_{osc}t)\right\} \\ &= \alpha_{fl}\eta(t) + \beta_{fl}\dot{\eta}(t) \end{aligned}$$

where, based on our assumption above, α_{fl} and β_{fl} are constants given by

$$\alpha_{fl} = |T_{fl}(j\omega_{osc})|\cos(\angle T_{fl}(j\omega_{osc}))$$

$$\beta_{fl} = \frac{|T_{fl}(j\omega_{osc})|\sin(\angle T_{fl}(j\omega_{osc}))}{\omega_{osc}}$$

A similar argument holds for the control path with the result that

$$\begin{aligned} F_c &= |T_{sp}(j\omega_{osc})||C(j\omega_{osc})|\, A(t)\sin(\omega_{osc}t + \angle T_{sp}(j\omega_{osc}) + \angle C(j\omega_{osc})) \\ &= \alpha_c\eta(t) + \beta_c\dot{\eta}(t) \end{aligned}$$

where,

$$\alpha_c = |T_{sp}(j\omega_{osc})||C(j\omega_{osc})|\cos(\angle T_{sp}(j\omega_{osc}) + \angle C(j\omega_{osc}))$$

$$\beta_c = \frac{|T_{sp}(j\omega_{osc})||C(j\omega_{osc})|\sin(\angle T_{sp}(j\omega_{osc}) + \angle C(j\omega_{osc}))}{\omega_{osc}}$$

The equation for the controlled, closed-loop system can be written as

$$\ddot{\eta}(t) + (2\zeta_{ac}\omega_o - a\beta_{fl} - \beta_c)\dot{\eta}(t) + (\omega_o^2 - a\alpha_{fl} - \alpha_c)\eta(t) = 0$$

where a term for the acoustic damping with damping ratio ζ_{ac} has been included. For stability we require the net damping to be positive. To insure that noise generated oscillations of the lightly-damped closed-loop system do not grow too large, it is further required that a minimum damping ratio ζ_{des} be achieved. This results in

$$2\zeta_{ac}\omega_o - a\beta_{fl} - \beta_c > 2\zeta_{des}\omega_{osc}$$

or

$$\beta_c = \frac{|T_{sp}(j\omega_{osc})||C(j\omega_{osc})\sin(\angle T_{sp}(j\omega_{osc}) + \angle C(j\omega_{osc}))}{\omega_{osc}} < 2\zeta_{ac}\omega_o - a\beta_{fl} - 2\zeta_{des}\omega_{osc}.$$

The right hand side of this inequality will be negative if we are adding damping to the system. Therefore, the minimum control signal will be achieved by picking a control phase such that the sin term is -1. This choice results in

$$\angle C(j\omega_{osc}) = -90° - \angle T_{sp}(j\omega_{osc})$$

$$|C(j\omega_{osc})| \geq \frac{\omega_{osc}|2\zeta_{ac}\omega_o - a\beta_{fl} - 2\zeta_{des}\omega_{osc}|}{|T_{sp}(j\omega_{osc})|}. \qquad (*)$$

Note that with this choice of phase angle, $\alpha_c = 0$ and so the application of control does not change the natural frequency of the thermoacoustic system.

To determine the maximum input excitation to the actuator, consider the hypothetical plot of limit cycle amplitude versus control magnitude, with phase fixed at the optimal value determined above, shown in Figure 14. At the crudest level of approximation, this would

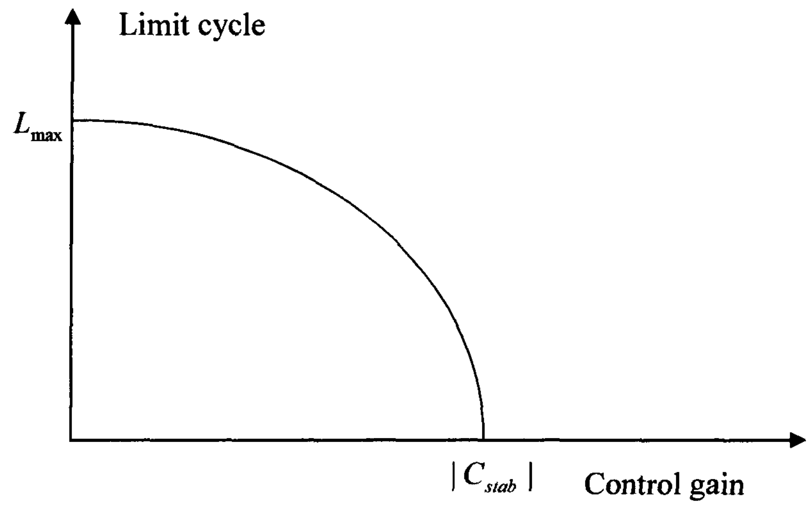

Figure 14: Limit Cycle Amplitude vs. Control Gain

require a maximum input to the actuator of $|C_{stab}|L_{\max}$. But to attain any point on the amplitude curve shown requires only an input of $gL(g)$, where g is the control gain and L(g) is the limit-cycle amplitude at this gain. Thus, the maximum input to the actuator to move from the uncontrolled state to the stabilized state is $\max(gL(g))$. Since we only know two points along the limit cycle amplitude curve, the zero gain point and the stabilizing gain point, assume that the curve varies linearly between these points so that

$$L(g) = -\frac{L_{\max}}{C_{stab}}g + L_{\max}.$$

This yields

$$\max_{g\in[0,C_{stab}]}(gL(g)) = \frac{L_{\max}C_{stab}}{4}$$

so the maximum input level to the actuator does not need to exceed this value to cause the system to be stabilized.

Computing the Stabilizing Gain

From equation (*) it is seen that the quantities needed to compute C_{stab} are the instability frequency, ω_{in}, the damping of the thermoacoustic system with no control, $2\zeta_{ac}\omega_o - a\beta_{fl}$, and the gain of the actuator transfer function between input voltage and measured pressure, $|T_{sp}(j\omega)|$. The instability frequency is easy to obtain by observation of the combustor limit cycle. The linear damping of the system cannot be determined from observation of the ultimate limit cycle, but requires observation of the growth of the instability. At the onset of the instability, when the system is operating in the linear regime, the instability amplitude will grow as $\exp(-(2\zeta_{ac}\omega_o - a\beta_{fl})t/2$. Thus, by observing the exponential growth curve, the required damping can be ascertained.

To determine the gain and phase of the speaker transfer function near the instability frequency, an experiment at a stable combustor condition near the instability condition needs to be performed. At this stable condition, the transfer function from control input to measured pressure in the frequency range near the lightly-damped modal resonance will have the form

$$\frac{|T_{sp}(j\omega_r)|\angle T_{sp}(j\omega_r)}{s^2 + 2\zeta\omega_r s + \omega_r^2}.$$

By measuring the frequency response at a number of points in the neighborhood of resonance, a curve fit can be used to find ω_r, ζ, $|T_{sp}(j\omega_r)|$, and $\angle T_{sp}(j\omega_r)$.

Results on the Rjike Tube

Experiments on the Rjike tube at an equivalence ratio of 0.55 and a mean flow of 120 cc/s show an instability at approximately 180 Hz. A simple phase shift controller can stabilize the system and the optimal gain is approximately 0.5 and the optimal phase is approximately 270°.

To attempt to predict this control result using the methodology above, measurements of the thermoacoustic damping and speaker transfer function were made. To measure the thermoacoustic damping, two approaches were used. In the first, the tube was run at an equivalence ratio that was near the equivalence ratio at which the system was unstable and we wished to achieve control. The equivalence ratio was then quickly changed to the ratio for instability and the growth of the instability was monitored. This resulted in a computed damping of -1.6. The second approach, which would not be applicable in practice, involved using control to stabilize the system at the equivalence ratio producing instability and then turning off the control and observing the amplitude growth of the instability. This method yielded a computed damping of -24.

Measurements of the speaker transfer function were made for both the cold tube and the hot tube running at a stable equivalence ratio. For the cold tube, the values produced by curve fitting were $\omega_r = 2\pi(164)$, $\zeta = 0.02$, $|T_{sp}(j\omega_r)| = 47000$, and $\angle T_{sp}(j\omega_r) = 170°$. This leads to a predicted optimal control phase of

$$\angle C(j\omega) = -90° - \angle T_{sp}(j\omega) = -260°$$

which is very close to the measured value.

The results of the stabilizing gain computation are shown in Table 1 below. Clearly the massive uncertainty in the thermoacoustic damping creates unacceptable uncertainty in C_{stab}. Considering the more accurate value due to turning off control at the actual instability condition, the computed value of C_{stab} is close to the experimental value of 0.50.

Table 1: Results of Stabilizing Gain Computation

$\|T_{sp}(j\omega_r)\|$	$2\zeta_{ac}\omega_o - a\beta_{fl}$	ζ_{des}	C_{stab}
47000	-1.6	0	0.0385
47000	-24	0	0.58
47000	-24	.01	1.28

The obvious critique of the analysis presented thus far is that the testing and methodology has been investigated only for a Rijke tube combustor using an acoustic actuator for control. However, these ideas will be expanded in the coming months to include the acoustic properties of the fuel injection systems described above, as well as the effects of the transition from modulated jet sprays to heat release rate.

Summary and Upcoming Work

The first nine months of the NRA research has been largely consumed by system fabrication, testing, and conceptual investigations that are required to support the ultimate goal of creating rapid characterization methods for unknown combustor systems. A new swirl LDI combustor has been designed and fabricated. This combustor can be operated in either thermoacoustically stable or unstable regimes. Flow rates have been optimized with respect to flame conditions and the strength of the instability when it exists. Two different modulating fuel injection systems, capable of proportional fuel modulation at flow rates in the range of 0.4 gph to 4.0 gph have been designed and are being tested at this time. Acoustic models of the fuel delivery systems for both injector designs have been completed and good agreement has been shown between the model and test results for most of the tested configurations. Flow measurements will soon begin, allowing correlation between upstream fuel line unsteady pressures and the actual modulation percentages measured in the nozzle sprays. Energy methods are under consideration, with the goal of determining minimum required "actuator" authority for any combustor of interest.

The next three months will complete the first calendar year of the NRA grant. The VACCG grant program is on progress in terms of its technical goals, as well as its budgeted expenditures. We look forward to continuing this research effort.

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13. ABSTRACT *(Maximum 200 words)*

The VACCG team is comprised of engineers at Virginia Tech who specialize in the subject areas of combustion physics, chemical kinetics, dynamics and controls, and signal processing. Currently, the team's work on this NRA research grant is designed to determine key factors that influence combustion control performance through a blend of theoretical and experimental investigations targeting design and demonstration of active control for three different combustors. To validate the accuracy of conclusions about control effectiveness, a sequence of experimental verifications on increasingly complex lean, direct-injection combustors is underway. During the work period January 1, 2002 through October 15, 2002, work has focused on two different laboratory-scale combustors that allow access for a wide variety of measurements. As the grant work proceeds, one key goal will be to obtain certain knowledge about a particular combustor process using a minimum of sophisticated measurements, due to the practical limitations of measurements on full-scale combustors. In the second year, results obtained in the first year will be validated on test combustors to be identified in the first quarter of that year. In the third year, it is proposed to validate the results at more realistic pressure and power levels by utilizing the facilities at the Glenn Research Center.

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