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ANNUAL LETTER REPORT FOR FY90

"Feedback Control of Combustion Instabilities: A Case Study in Active Adaptive Control of Complex Physical Systems"

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1. Objectives

This program will address the following issues:

- Previous studies on small (1-kW), premixed, gas-fueled combustors have demonstrated suppression of longitudinal mode combustion instability using pressure (or heat release) feedback and loudspeaker modulation. Can the same results be achieved on a larger scale (200 kW), liquid-fueled combustor using a more practical actuation means?
- Owing to the high order and nonlinear nature of the processes involved, we would expect that a single, linear, time-invariant (LTI) controller would be capable of stabilizing the combustor over only a small range of airflows and equivalence ratios. What are the relative merits of adaptive versus non-adaptive control strategies for extending the operating regime of the controller?

2. Approach

To provide a research test bed, we will modify a 3-in by 3-in, premixed gas combustor to accept liquid fuel admitted through a high bandwidth, Moog servo valve. Fuel flow modulation will be tried first as a means of actuation. If necessary, a fuel pressure feedback loop will be closed around the valve to extend its bandwidth even further. We will then obtain a "screech map" by measuring the combustor pressure power spectrum at several combinations of airflow rates and equivalence ratios. Based on these measurements, and on our experience with the 1-kW combustor, we will select a screeching operating point at which to begin the control system design.

No rigorous, *rational* method exists for designing a controller to stabilize a poorly known, unstable system. To begin the controller design, therefore, we will use one or more of the following *ad hoc* procedures:

(1) At the target operating point, *while the combustor is screeching*, measure the process frequency response from fuel flow input to combustor pressure output using the swept sine technique. Use standard computational methods to identify the poles and zeros of the underlying transfer function (the poles will all be stable). Modify this transfer function by selecting a pair of complex conjugate poles whose natural frequency is in the neighborhood of the *screech frequency and reflecting* that pair through the imaginary axis to obtain a pair of unstable poles. With this modified transfer function as the process model, use any appropriate design technique (e.g., classical loop shaping, pole placement, LQG/LTR) to obtain a stabilizing compensator. (This technique has succeeded at two operating points of the 1-kW, gas-fueled combustor. It is not foolproof, however, having failed at two others.)

(2) Use an all-pass filter controller structure, and tune the filter's gain and phase roll-off frequency, in real time, by trial-and-error. (This technique has also worked for some 1-kW combustor regimes and failed for others.)

(3) At a non-screeching equivalence ratio near the target operating point, measure the process frequency response and identify a pole-zero model. Use pole placement techniques to design a compensator to improve the system's relative stability by moving the closed loop system poles away from the imaginary axis. Use this same controller at the unstable target operating point. (This approach is original to this program.)

Having thus obtained a stabilizing compensator, we can then directly measure the true, small signal, process frequency response about the unstable target operating point. Based on a model identified from this response, we will re-design the controller to improve its robustness, and then experimentally determine the range of flows and equivalence ratios for which the closed loop system is still stable. At an operating point near the fringe of this stability region, we will measure a new frequency response, identify a new process model, and design a new stabilizing LTI controller. In this manner, we will "bootstrap" our way across a large portion of *the combustor operating envelope, accumulating LTI* compensators as we go.

Methods of combining these several compensators into a unified, full-envelope controller will then be investigated. These will include non-adaptive approaches, such as parameter scheduling, as well as adaptive techniques, such as self-tuning and model-reference methods. The first of these attempts will probably be a self-tuning design that simply automates the design procedure described above.

While some of the LTI compensators may be simple enough to permit analog implementation, most will probably be of sufficient complexity to warrant computer implementation, and the final scheduled or adaptive controller is certainly this complex. Since no currently available turnkey system can achieve the required throughput, it will be necessary, therefore, to configure a custom computing platform on which to implement these designs.

3. Accomplishments During FY90

The most significant accomplishments for this year are as follows:

(1) Extended fuel flow bandwidth to 220 Hz by closing fuel pressure feedback loop around the Moog servo-valve.

(2) Obtained quantitative combustor screech map—detailed power spectra at 23 combustor operating points.

(3) Designed, implemented, and tested *unsuccessful* analog controller designs using *ad hoc* procedures (1) and (2) at one operating point and using procedure (1) at another. (These procedures are described in section 2, above.)

(4) Designed and integrated custom computing platform for implementing high order, self-tuning regulators. The design target was an 18th order, single-input, single-output, recursive filter with a 10-kHz sampling rate.

Figure 1 is a schematic of the experimental setup used for making frequency response measurements on the 200-kW, liquid fueled combustor. Sensors labeled P_2, P_3, P_4 are pressure transducers; the sensor labeled D_6 is a lens-filter-photomultiplier tube assembly tuned to a spectral line of the combustion reaction. The "Valve controller" is an electronic circuit board, supplied by Moog, with space for adding custom compensation between the feedback voltage, V_7, and the controller output voltage, V_{13}. Two input voltages, V_1 and V_6, are summed to form the total valve set point; here, we use V_1 to provide a DC bias fuel flow, thus establishing the nominal combustion equivalence ratio, and V_6 to provide the control input. The "Servo-valve" maintains a valve opening proportional to its coil current which is, in turn, proportional to V_{13}. Depending on the experiment being run, the block labeled "Process controller" serves different functions; in most cases, it is a simple collection of operational amplifiers built on a plug-in prototyping board. In the experiment shown—the setup for measuring the closed-loop response of the fuel control—the process controller is just a wire, passing its set point input directly to the output. To measure the frequency response, we connect an HP-3562 "Dynamic Signal Analyzer" as shown; the analyzer provides a sinusoidal excitation and measures the resulting frequency response, $Y(j\omega)/X(j\omega)$,[1] in this case, the fuel pressure output response, P_2, due to set point input, V_6.

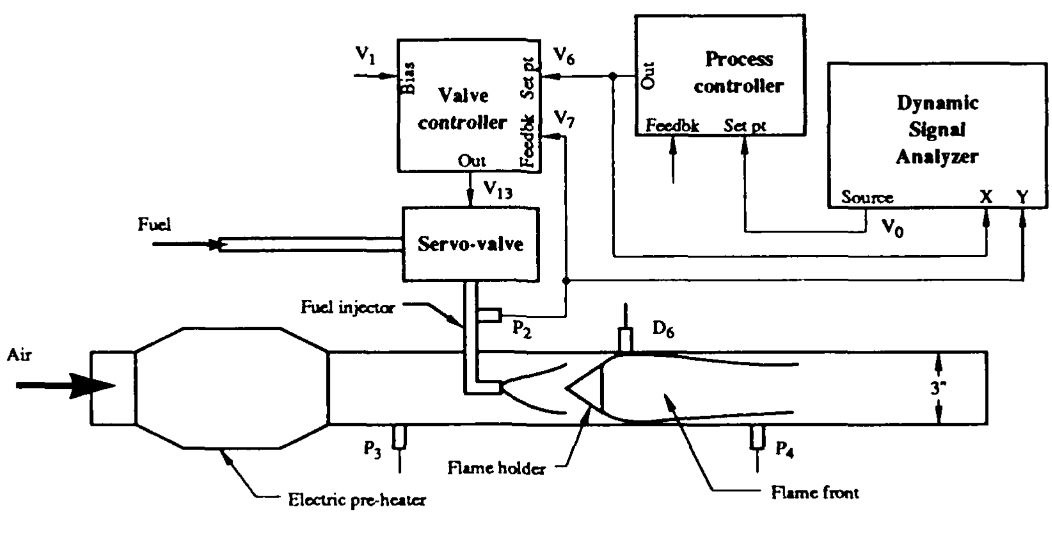

Figure 1. Setup for frequency response measurements.

The dashed curves in Fig. 2 are the closed-loop frequency response of the fuel pressure, $P_2(j\omega)/V_6(j\omega)$; the solid curves are the response of the uncontrolled valve, $P_2(j\omega)/V_{13}(j\omega)$. Whereas the uncontrolled system begins to roll-off at about 30 Hz, adding custom compensation (a simple gain of 2) and closing the loop yields a flat response with a

1. $j = \sqrt{-1}$, and ω = frequency.

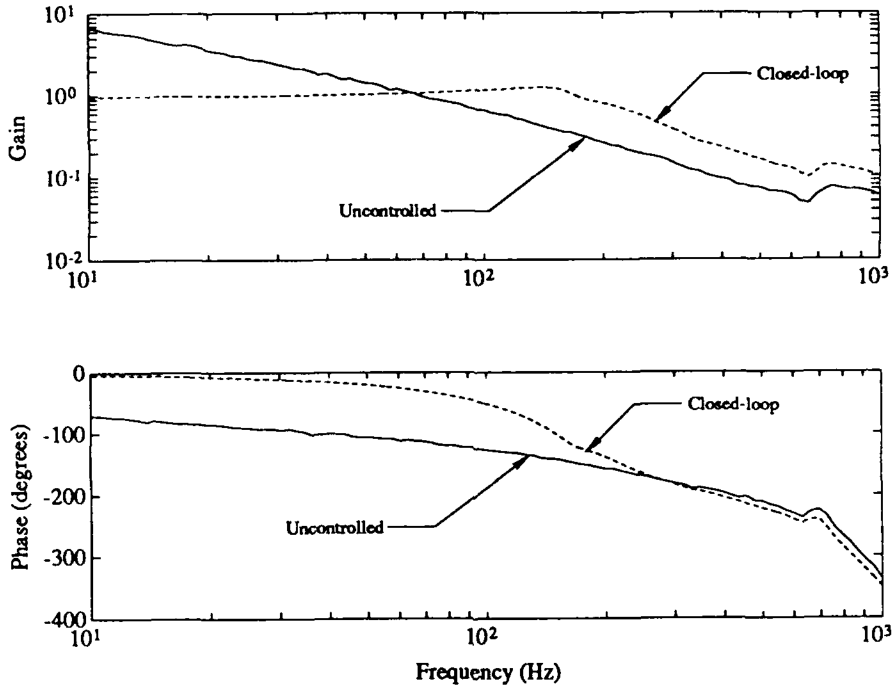

Figure 2. Moog servo valve frequency response.

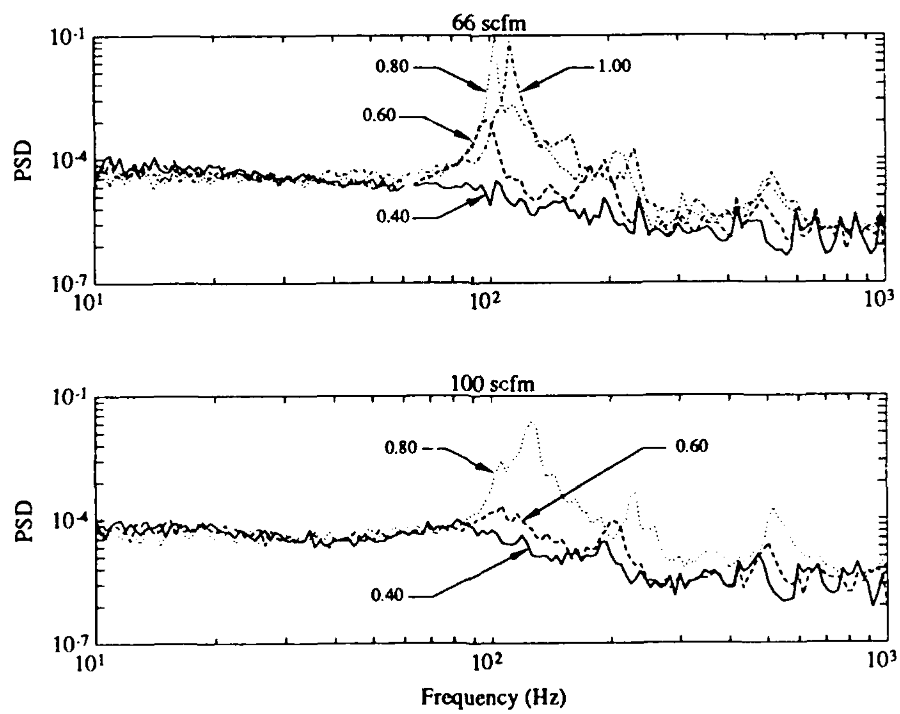

Figure 3. Liquid-fueled combustor screech map.

-3 db point at 220 Hz.

Figure 3 is an excerpt from the quantitative screech map of the liquid-fueled combustor. Airflows (Q) are labeled in the graph titles, while the individual curves are labeled with their equivalence ratios (ϕ). The entire data set consists of power spectrum measurements of P_3 (see Fig. 1.), taken at the following sets of operating conditions: Q = 66 scfm, $0.40 \leq \phi \leq 1.00$, in steps of 0.05; and Q = 100 scfm, $0.35 \leq \phi \leq 0.80$, in steps of 0.05.

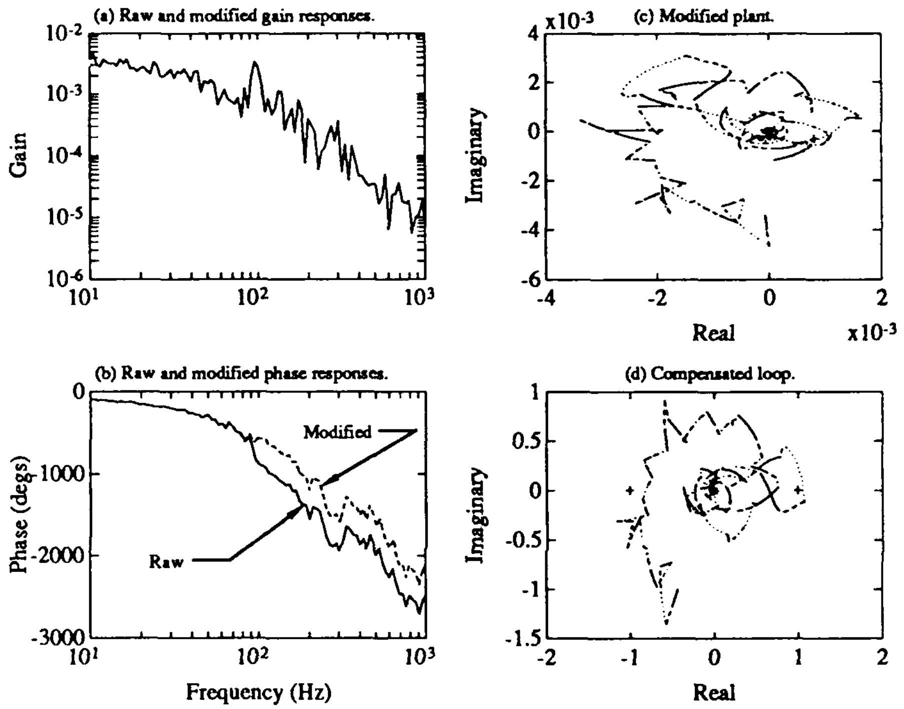

Figure 4. Controller design at one target operating point.

Figure 4 documents one of the attempts at a controller design using *ad hoc* procedure (1); the operating point is Q = 66 scfm, $\phi = 0.70$. First a measurement of the process frequency response, $G_1(j\omega) = D_6(j\omega)/V_6(j\omega)$, was obtained; this is the solid line in Figs. 4(a) and 4(b). Next, using the analyzer's peak identification function, the pole pair responsible for the peak near 100 Hz was identified as $-2.5\text{Hz} \pm j94.6\text{Hz}$. We then synthesized the frequency response

$$M(j\omega) = \frac{(j\omega + 2.5 + 94.6)\ (j\omega + 2.5 - 94.6)}{(j\omega - 2.5 + 94.6)\ (j\omega - 2.5 - 94.6)} \tag{1}$$

for $10 \leq \omega \leq 1000\text{Hz}$, in order to generate the modified frequency response, $G_2(j\omega) = M(j\omega)G_1(j\omega)$, shown as the dashed line in Figs. 4(a) and 4(b) and as a Nyquist plot (positive frequencies only) in Fig. 4(c). The two responses are identical except that where G_1 has a stable pole pair near 100 Hz, G_2 has an unstable pole pair. Examining Fig. 4(c), we can see that the unstable pole is manifested as the counterclockwise oriented loop at the topmost center of the plot. (The sequence of line styles corresponding to increasing frequency is solid, dashed, dotted, dot-dashed.) In order to stabilize this system, using *positive* feedback, this loop must be made to encircle the critical point, $1 + j0$. Using classical loop shaping design techniques, a compensator,

$$H(j\omega) = \frac{j\omega - 50}{j\omega + 50}, \qquad \omega \text{ in Hz}, \tag{2}$$

was designed to stabilize G_2. The Nyquist plot of the compensated loop, $G_2(j\omega)H(j\omega)$, with $H(j\omega)$ as measured from the circuit implementation, is drawn in Fig. 4(d). Evidently, the required encirclement is achieved so that, if the assumptions underlying the construction of G_2 are correct, this compensator ought to stabilize the combustion process. Unfortunately, the resulting closed loop system was *not* stable. Since this controller is an all-pass filter, it was an easy matter to try *ad hoc* procedure (2) by adjusting the filter's phase roll-off frequency and gain in real time. This procedure, too, failed to yield a stabilizing controller. Another attempt at using procedure (1) was made at the operating point $Q = 100$ scfm, $\phi = 0.70$. Here the stabilizing controller ought to have been a simple gain of about 800. However, this closed-loop system was also still unstable.

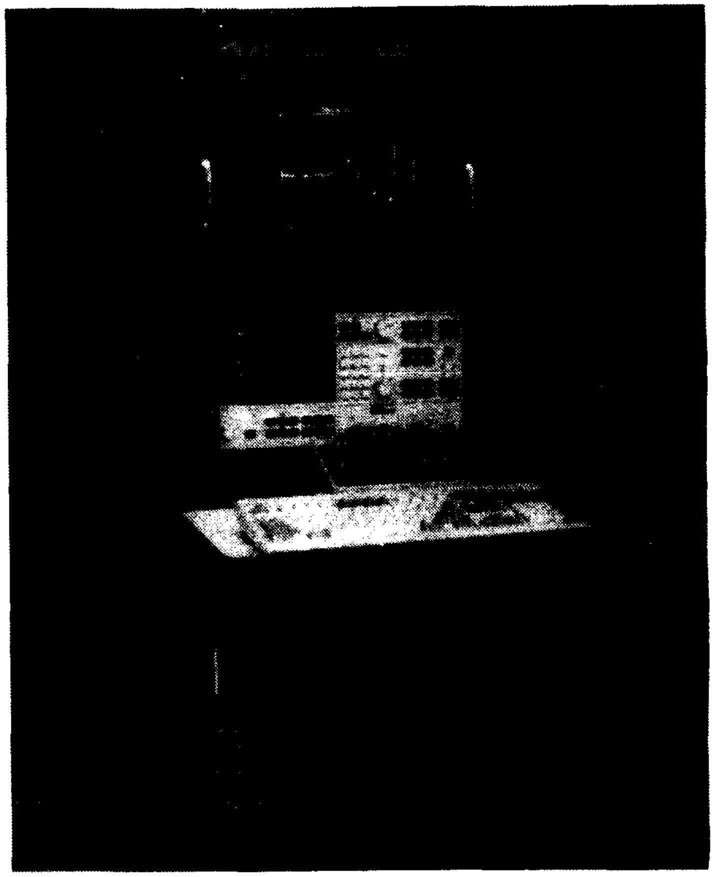

Figure 5. Custom integrated computer platform.

Figure 5 is a photograph of the data acquisition and control system designed this year, which we expect to exercise next year. Mounted in a standard, 6-ft tall, 19-in rack the system comprises (from the top in Fig. 5) an HP-GL graphics plotter, a color monitor, an HP-3563A Control Systems Analyzer (the next improved model from the one used this year to acquire and analyze the frequency domain data), a standard keyboard, and (below the shelf) the custom integrated control computer. The computer and the analyzer communicate via IEEE 488 interface, while the computer is also connected to our center-wide computing resources via Ethernet. The custom computer consists of an IBM 386 PC host, sharing a passive backplane with two Atlanta Signal Processing Banshee digital signal processing boards, and two Data Translation analog I/0 cards. In its final configuration, the two DSP boards will run independently of the host PC—one implementing a high order, recursive digital filter to achieve the process stabilization; the other continually identifying the process dynamics, re-designing the stabilizing filter, and downloading the filter parameters through shared memory. The black box on the table-top, next to the keyboard, is an "analog combustion simulator" designed for this project. The box implements the general, second-order transfer function

$$y(s) = K\frac{As^2 + Bs + C}{s^2 + Ds + E}u(s) \tag{3}$$

where the coefficients, K, B, C, D, E can each be either positive or negative, and have their magnitudes variable, to three-digit precision, in a range suitable for simulating frequencies between 50 and 5,000 Hz; the value of A is either 0 or 1. We intend to use this simulator to provide a known, variable plant on which to test the digital, self-tuning regulator.

4. Significance of FY90 Accomplishments

The primary significance of this year's accomplishments is that they are all necessary preparation for achieving the program objective of demonstrating full-envelope, feedback stabilization of combustion instability using a practical means of actuation. The failure of the three controller designs described above is not cause for alarm; these designs were constrained to be simple, analog circuits so that only procedures (1) and (2) were feasible. Procedure (3), however, resting on a surer theoretical footing, is still likely to succeed. With the completion of the custom integrated computing platform, we will be able to implement the complex controllers resulting from this approach.

5. Presentations, publications, etc.

1. A. Gulati and R. Mani, "Active Control of Unsteady Combustion-Induced Oscillations," Proc. 28th AIAA Aerospace Sciences Meeting, Jan. 8-11, 1990, AIAA-90-0270.

6. Program participants

The following GE people contributed to this program:

Dr. Anil Gulati	Aeronautical Engineer
George Goodman	Control Systems Engineer
Dr. Ramani Mani	Fluid Dynamicist
Dr. Paul K. Houpt	Control Systems Engineer
Dr. Lawson Harris	Electrical Engineer
James Bedard	Electronics Engineer