OPTIMAL CONTROL OF SWIRL STABILIZED SPRAY COMBUSTION USING SYSTEM IDENTIFICATION APPROACH

S. Murugappan[1], S. Park[2], S. Acharya[1], A.M.Annaswamy[2], E.J. Gutmark[3], and A.F. Ghoniem[2]
Mechanical Engineering Department
[1]Lousiana State University, Baton Rouge, LA 70803
[2]MIT, Cambridge, MA 02139
[3]University of Cincinnati, Cincinnati, OH 45221

ABSTRACT

Introduction

The suppression of themoacoustic instabilities is one of the major challenges in the design and development of high performance combustors. The coupling of the fluid dynamic instabilities with the acoustic mode of the system drives the combustor to a thermoacoustic resonance which are responsible for large scale pressure and heat release oscillations. Active control strategies are based on continuously perturbing a specific combustion parameter to dampen the amplitude of the limit cycle. Active methods can be classified as closed loop or open loop depending upon whether or not feed back from the combustor influences the perturbations. Open loop controllers provide a fixed stimulus to the combustor in order to decouple the physical mechanisms responsible for the instability. Closed loop systems utilize a sensor signal to apply an appropriate control action to the actuator. For example, Lang at al[1] used a loudspeaker modulating the airstream with a phase opposite to that of the pressure oscillations (antisound). Murugappan et al.[2] recently have used a phase-delay modulation of the fuel stream to decouple the heat release oscillations from the pressure oscillations. There are several other studies where similar active control strategies have been employed.

The present paper deals with the demonstration of an LQG-LTR (Linear Quadratic Gaussian-Loop Transfer Recovery) technique applied to suppress pressure oscillations in a swirl stabilized spray combustor. System identification methods were used to identify the modes in the combustor at different operating conditions. Both phase delay and LQG-LTR controllers were implemented at these flow conditions. The performance of these controllers were evaluated based on the reduction in the rms pressure fluctuation levels.

The experiments were performed in a swirl-stabilized combustor operating at 30 kW heat release. The combustor had a central fuel feed and a coaxial primary and secondary air streams injected in a co-swirl mode. Ethanol was used as the liquid fuel. It was pressurized to 120 psi in a fuel tank by high-pressure inert nitrogen, metered, and supplied to a Parker-Hannifin research simplex atomizer (RSA) nozzle through a tube mounted in the center of the air chamber. The average fuel flow rate was kept constant at 0.75 ml/sec. Primary air with a flow rate of 0.056-0.283 m^3/sec, at five atmospheres, was used to atomize the fuel. The fuel stream was modulated using an automotive fuel injector driven by a signal processor. Secondary air, also at five atmospheres, was introduced co-axially around the nozzle with a flow rate that varied from 0.283-1.7 meter^3/sec. The combustion shell was L=0.6 meters in length and D=0.14 meters in diameter. High sensitivity, water-cooled pressure transducer was mounted along the length of the combustor to measure the oscillations in the combustor for varying flow rates and fuel flow modulation frequencies. The pressure sensors was located at a normalized axial distance z/D=1.45.

A high-speed microprocessor was used to perform real time signal processing. The hardware consists of a super scalar microprocessor Motorola power pc 604e running at 333 MHz and a slave DSP TMS320F240 at 20 MHz clock rate. Code generation, compiling and downloading was done with Simulink and Dspace real time interface. The pressure fluctuations, which were recorded from the high sensitivity pressure sensor, was fed into the ADC. The digital signal was amplified and phase shifted with respect to the fuel injector signal, band pass filtered and then sent to the DAC. The signal written to the DAC was fed into a solid-state relay powered by a battery to run the automotive fuel injector. Initially the fuel actuator frequency was matched with the instability frequency, which was used as a driving signal for the fuel injector. It was then switched to operate on the control signal once the first set of data was processed for every preset phase angle. Phase angles were initially varied over one instability cycle to detect the optimum delay corresponding to the maximum suppression. Subsequently, an LQG-LTR controller was implemented to demonstrate its effectiveness over phase delay control.

Results and Discussions

System identification methods were employed to study the characteristics of the fuel injector and the combustor. These system identification studies were then used to build a LQG-LTR controller. For the system ID studies, the injector was modulated with a psuedo random binary sequence (prbs) signal low pass filtered at 400 Hz. The response from the injector was measured at the exit of the nozzle with a hot film anemometer. The injector shows the presence of two broadband frequencies, one around 0-25 Hz and other ranging between 300-350 Hz. These preferential bands excited by the injector were filtered to control only the combustor modes in the closed loop control studies. A similar identification procedure was performed in reacting flows. Three sets of operating conditions were chosen to demonstrate closed loop control. The fuel injector was provided with a prbs low pass filtered at 400 Hz and the response was recorded by a pressure transducer at the three operating conditions. The combustor shows the presence of unstable longitudinal mode in the range of 200 – 230 Hz. Figure 1 shows the frequency spectra for a typical uncontrolled condition. Two broadband peaks as noted in cold flow studies was also present in reacting flows. The power spectral density plots indicate peaks in the 200-250 Hz range. Phase delay control was initially implemented at three flow conditions (Φ=0.5, 0.55, 0.74 and referred to as cases 1, 2 and 3 respectively). Reduction levels corresponding to 8, 12 and 19 dB were achieved with phase delay control for the three cases (cases 1, 2 and 3) respectively. Next an LQG-LTR controller was tested at these flow conditions. System identification methods were used to obtain the plant transfer function. Different models such as ARMAX, ARX, N4SID were applied to extract the combustor model. Best model was chosen by optimizing the order of zeros, poles time delay and the error between the measured and observed pressure sensor signal. The 11th, 6th, 10th order controllers were identified to be the optimum controllers for cases 1 2 and 3 respectively. Figure 2 shows the power spectral plots for the base line, phase delay and LQG-LTR controller pressure response for case 1 (Φ=0.5). The LQG-LTR controller showed better reductions in pressure levels for this case (figure 10) as well as for cases 2 and 3. Compared with the optimum phase delay control, the LQG-LTR reduced pressure oscillations by a 12-14 dB greater margin. It is to be noted that higher order controllers like loop shaping H∝, and LQG-LTR controller require larger computational times, but provide better performance

Reference

1. Lang, W., Poinsot, T., and Candel, S., Active control of nonlinear pressure oscillations in combustion chambers, *Journal of Propulsion and Power*, Vol. 8, No. 6, pp. 1282-1289, 1992.

2. Murugappan, S., Acharya, S., Gutmark, E. J., and Messina, T., Characteristics and control of combustion instabilities in a swirl-stabilized spray combustor, *AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit,* Los Angeles, CA, June 20-24, 1999

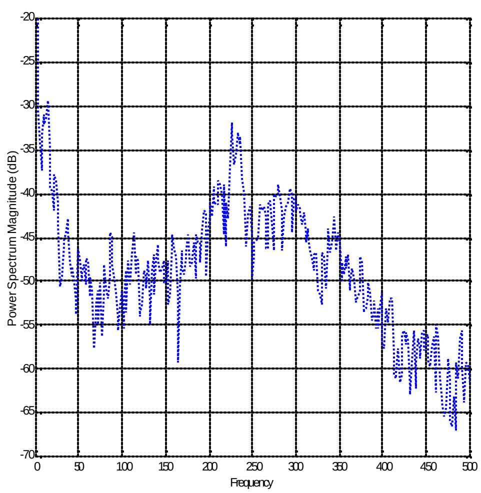

Figure 1: Pressure spectra for the uncontrolled combustor. Note the dominant peak at around 230Hz representing combustion instability.

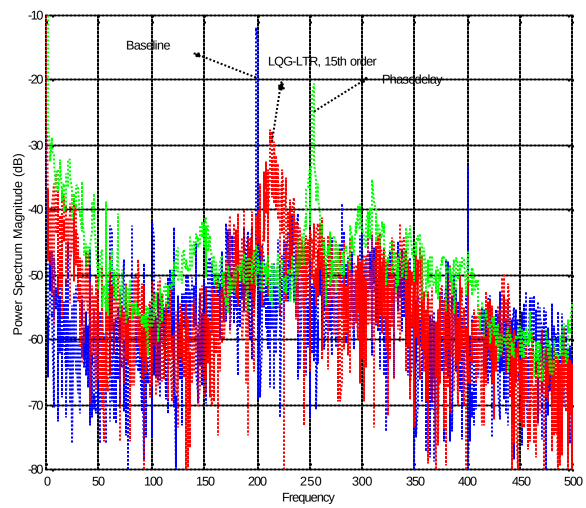

Figure 2: Comparison of the pressure spectra: uncontrolled (baseline), phase-delay control, and LQG-LTR control. Note the freater reductions in pressure oscillations with the LQG-LTR control.