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An Experimental Study on Actively Controlled Dump Combustors

K. Yu
Aerospace Engineering Department
University of Maryland
College Park, MD 20742, USA
email: yu@eng.umd.edu

and

K.J. Wilson, T.P. Parr, and K.C. Schadow
Research Department
Naval Air Warfare Center
China Lake, CA 93555, USA

A closed-loop liquid-fueled active control technique was applied in a dump combustor to enhance its combustion performance. Practical issues involving liquid fuel, scaling effects, and affordable control methods were studied experimentally. The results shed new light on the requirement of critical fuel flux, effects of fuel droplet size on control, and novel controller concepts, that would help the future development work. The critical fuel flux was found to be dependent on the fuel droplet size and initial magnitude of the instabilities. When the fuel droplet size, D_0, was reduced in the controlled injection, the control efficiency for heat flux actuation increased significantly. The analysis yielded an exponential dependency on the droplet size. For a moderate droplet Reynolds number considered in this study, the amplitude of controlled heat release for a given fuel amount was inversely proportional to the droplet size by a factor of $D_0^{-1.4}$. Also, two novel controller concepts, which incorporated practical designs, were tested and were shown to work effectively compared to the baseline case. One of the concepts was based on injecting fuel pulses at sub-harmonic frequencies of the instability, thus addressing the limited actuator frequency response. The other concept utilized both open-loop and closed-loop control schemes to obtain enhanced performance including extension of the stable combustion zone. These results open up the possibility of applying the active combustion control technology to advanced propulsion devices.

1. Introduction

While there has been a renewed interest on active combustion control (ACC) stemming from increasingly restrictive requirements on gas turbine pollution, many of the earlier studies on ACC were motivated by the desire to improve combustion performance in rockets, ramjets, and afterburners. [1] Past studies on active combustion control (ACC) have shown that it is possible to enhance combustion performance through fast-response closed-loop feedback control. [2,3] The scope of earlier investigations, however, often remained relatively basic in nature making it difficult to transition such research results into a practical system. In this paper, we attempt to address some practical issues that will provide the scientific basis for ACC implementation in practical systems. More specifically, various scaling and implementation issues are examined as well as the latest development in our active control study.

Some of the previous studies in this area include instability suppression, [4-13] efficiency improvement, [11-16] flammability limit extension, [11-13,17] and pollutant reduction. [11,15,16,18-19] These studies have opened up the opportunity to study more practical issues related to potential implementation of ACC in real systems. In this paper, we consider applying ACC in a liquid-fueled dump combustor. Such combustors could be used in advanced ramjets, gas turbines, or afterburners. The objectives are to better understand the physical processes and mechanisms involved in liquid-fueled active combustion control and to explore a practical ACC design based on pulsed liquid-fuel injection, that may be suitable for future ramjet combustors. The scope of the present paper is mostly limited to considerations involving instability suppression. However, a result showing flammability limit extension will also be presented at the end.

The result section will include two parts. The first part will describe the general progress on the study of liquid-fueled combustion control. Because of complexity associated with heterogeneous nature of liquid-fueled combustion, it is difficult to use liquid fuel in combustion control. Also, control efficiency needs to be maximized via direct injection into the combustion chamber. The first part will, therefore, include the investigation on the underlying physical processes as well as on some scaling

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issues. Then, in the second part, we will turn our attention to the latest research results, which involve practical control and actuation strategy. Two novel techniques are introduced that were meant to address potential discrepancy between actuato frequency response and combustor dynamics. Also, more efficient control process involving open- and closed-loop control systems will be described.

2. Active Control System

The experiments were performed in a 102-mm diameter axisymmetric dump combustor with adjustable inlet and nozzle dimensions. The inlet tube was 42 mm in diameter (ID) and the length was between 20 to 60 diameters. Table 1 summarizes the combustor and inlet dimensions for several different cases that have been tested so far. The main fuel, ethylene, was injected through a choked orifice at a 90-degree angle to the oncoming flow. The injection location was 16 inlet diameters upstream of the dump plane causing the inlet flow to be well-mixed entering the combustor. Relatively small amount of liquid fuel was injected directly into the combustor using pulsed fuel actuators. The pulsed fuel injection was closed-loop controlled to affect the dynamics of the reacting flow. Figure 1 shows a picture of the rig with some of the control system components labeled for reference. The controller was operated from inside the control room which is not shown.

Figure 2 shows the control system architecture that was used to control the fuel injection scheduling into the dump combustor. For active instability suppression, the initial approach we had taken was to pulse the liquid fuel at the instability frequency and adjust the timing using a simple closed-loop circuit (Fig. 2a). Because our emphasis was on extending active control to liquid-fueled combustors, a simple phase-delay circuit was utilized instead of a more sophisticated controller, such as those based on an adaptive technique [20] or model-based design approaches [21-23]. Figures 2(b) and 2(c) show the development of more practical controller circuits. First in Fig 2(b), a divider was added to the circuit of Fig 2(a). This allowed periodic injection of fuel at sub-harmonic frequencies of the instability frequency. This would be particularly advantageous if the actuator frequency response was limited in the low frequency range below the characteristic frequencies of the combustor. Also, another novel concept was tested which is based on establishing a controlled amount of oscillations by combining an open-loop injection control with a closed-loop control. The "Output 1" in Fig 2(c) was used to drive one-half of the injectors at the driving frequency f_0, which was one of either harmonic or sub-harmonic frequencies of the instability. Then, a second set of controller was used in a closed-loop fashion to control the amplitude of oscillations. The closed-loop controller in this case was based on time-delayed proportional control concept.

A Kistler™ pressure transducer, mounted at one inlet diameter downstream of the dump plane, was used to detect the oscillations in combustor pressure. Then, with the combustor pressure signal as reference, the phase shift for the injection cycle was digitally controlled using a Wavetek™ Variable Phase Synthesizer. The liquid fuel was injected through the four fuel actuators that were spaced 90 degrees apart along the circumference of the inlet at the dump plane.

The initial injection angle was fixed at 45 degrees with respect to the air flow direction after a parametric study that investigated the most desirable angle for this set of actuators in utilizing flow-droplet interaction. [24] However, in Case 5, another set of actuators that utilized air-assisted atomization mechanism was explored to investigate the effect of droplet size on combustion control ability.

The first set of actuators was a combination of "off-the-shelf" automotive fuel injectors and swirl-based atomizers [25] with 300 µm exit diameter. Such a combination allowed reasonably small fuel droplet size with relatively high frequency response. The second set of actuators consisted of prototype pulsed fuel injectors, that utilized air-assisted atomization mechanism. The latter injectors produced much finer droplets but their frequency response was limited to below 150 Hz. [26] Table 2 summarizes the some of the physical parameters and flow conditions for the actuated experiments.

3. Part I -- Fundamental Results and Progress

With recent advances in actuator technology and enhanced understanding of the involved physical processes, the major emphasis of the present investigation was to concentrate on practical issues involving system integration and components development. The first part of the study was conducted to understand the liquid-fuel related issues and the effect of scale-up, while the second part addressed the development of practical control strategy.

In the first part, the timing of pulsed fuel injection was adjusted using a simple phase delay controller. The injection frequency was matched to that of the oscillation frequency. The fundamental mechanisms associated with liquid-fueled combustion control were investigated.

3.1 Vortex-Droplet Interaction

First, it was necessary to utilize the interaction between fuel droplets and large-scale flow features to disperse the fuel to the desired location. As expected, periodic vortices were shed during the oscillation cycle. [27] Because both the fuel injection and vortex shedding processes were periodic, adjusting the timing between the two resulted in controlled interaction between the transient processes. This mechanism was utilized in the experiments. Figure 3 shows the phase-dependent fuel dispersion behavior over one full cycle of flow oscillation. Depending on the relative timing of pulsed fuel injection, the fuel droplets are distributed in the different parts of the combustor.

The extent of the interaction between fuel droplets and vortices can be expressed in terms of the droplet Stokes number

$$Sto = \frac{\rho_f D^2 F}{18\,\mu_g} \qquad (1)$$

where D is the droplet diameter, F the vortex frequency, ρ_f the droplet density, and μ_g the gas viscosity. On one hand, it was desirable that *Sto* be of the order of unity or higher for controlling the dispersion of fuel droplets in space, as larger droplets are less influenced by fluid motion. Recent experiments [28-30] and computations [31,32] suggested that only those droplets with *Sto* on the order of unity are affected by fluid motion and yet have enough momentum to be dispersed further outside the carrier fluid path. On the other hand, for combustion control purpose, finely atomized droplets with very short combustion delay were desirable. Thus, a desired fuel droplet distribution was such that the droplets with *Sto* close to unity constituting the upper end of the size spectrum.

In the experiments, however, the actual distribution of fuel droplet size was determined by the given actuation hardware and was difficult to control in a systematic manner. Thus, two different sets of actuators with substantially different atomization characteristics were employed to study the effect of fuel droplet size on combustion control ability and limit.

3.2 Controlled Heat Release Requirement

It is plausible that a certain minimum amount of acoustic energy is required to obtain control authority in practical flows. Because the combustion-acoustic interaction is a dominant source of acoustic energy generation in the present system, the amplitude of heat release must be considered. Assuming that acoustic energy can be controlled using Rayleigh's criterion, the amount of acoustic energy is directly proportional to the amount of controlled heat release. For instance, the change in local acoustic energy after one period T is given by

$$\Delta\varepsilon \approx \frac{\gamma - 1}{\gamma} \int_t^{t+T} \frac{p' \cdot q'}{\bar{p}}\, dt \qquad (2)$$

where p' denotes the time-dependent pressure fluctuation, q' local heat release fluctuation, γ the ratio of specific heats, and p the average pressure. The Rayleigh's criterion illustrates the timing between the pressure fluctuation p' and the controlled heat release q'. The controlled amount of heat release is a function of fuel droplet size as well as fuel amount. For a given amount of fuel, the dependency on droplet size can be modeled [33] and the result is given by

$$|q'|_{\max} \approx \text{Constant} \times \frac{\Delta T}{h_{fg}} D_0^{-1.4} \qquad (3)$$

where • T is the temperature difference between the fuel and the surrounding flow, h_{fg} latent heat of vaporization, and D_0 the initial droplet size. This implies that pulsed fuel sprays with smaller droplet size will be more effective in generating controlled heat flux oscillations.

The amount of acoustic energy needed for control authority, however, will also depend on the initial magnitude of the instabilities. In the next section, the results of the investigation on the critical fuel flux for two different actuator characteristics are presented. Then the results are normalized with respect to the instability magnitude to verify the applicability of Eqn. (3).

3.3 Critical Fuel Flux

In the actuated combustor experiments, the initial distribution of fuel droplet size was determined almost entirely by the actuator characteristics. For each set of actuators, the minimum amount of fuel flux, which is required for obtaining active instability suppression, was determined. For this purpose, the amount of controller fuel flux was held constant while the overall power output was increased until the instability was no longer controllable. With No. 1 actuators (Cases 1 through 4), which generated about 40 μm Sauter-mean-diameter droplets, this point was reached when the relative amount of controller fuel flux dropped below 8% of the total average fuel flux. At this point, the instability amplitude was no longer suppressed by actively controlled fuel injection.

No. 2 actuators, on the other hand, were more efficient as they produced much finer fuel sprays. Figure 4 shows the comparison between the uncontrolled case in which all the fuel was premixed and the controlled case with the properly phased closed-loop fuel injection. As before, if the relative phase of fuel injection was not properly controlled, however, the oscillation amplitude could become as intense as the uncontrolled case. Figure 4b shows the oscillation amplitude at a few pre-selected electronic phase delay settings. Even at the highest output case tested, the instability was controllable with these actuators. Therefore, the number of actuators was reduced to determine the critical fuel flux. When the controller fuel flux was lowered to an amount below 2% of the total fuel flux, the instability suppression became no longer feasible even with the No. 2 actuators. Figure 5 summarizes these results as a plot of controller fuel flux .vs. the controlled oscillation amplitude.

The results for two actuators were compared by normalizing the results with respect to the initial magnitude of the instability. For this purpose, the theoretical amount of controlled heat release required to suppress the given instability in one cycle was calculated [33] from Eqn. (2).

$$|q'|_{theoretical} \approx \frac{f}{2(\gamma-1)}\left[\frac{\left(\bar{\rho}\, c\, |u'|_{instability}\right)^2}{|p'|_{instability}} + |p'|_{instability}\right] \quad (4)$$

Figure 6 shows the normalized results for these cases. The amount of potential thermal energy, associated with pulsed amount of fuel, was normalized by the reference heat release amount given by Eqn. (4) The comparison of the critical fuel flux for the two actuators shows that the No. 2 actuator is more efficient than the No. 1 actuator by a factor of 6. In other words, the normalized limit data indicate that the No. 2 actuators produced 6 times higher heat release modulation than the No. 1 actuators due to their droplet size difference. The expected value of efficiency improvement, which is based on the droplet size comparison of Eqn. (3), yields a factor of 7 between the two cases. Considering the difference in actuator configurations, the results are in good agreement.

4. Part II -- Practical Control Experiments

The second part of the experiments focused on the practical control issues. Two novel ideas were introduced and tested for validation. The first was based on the use of actively controlled fuel injection at sub-harmonic frequencies. Because the instabilities may occur at frequencies higher than the frequency response of the actuators, a more practical solution was sought. The controller circuit, which was shown in Fig. 2b, was constructed to drive the actuator unit at the first sub-harmonic frequency of the instability.

The second idea addressed the problems associated with multi-mode instability frequencies. It was observed in our earlier study [34] that a simple phase-delay circuit may not be very effective if the instability frequency shifts by more than the predetermined setting of the bandpass filter. To more effectively control the combustor dynamics over a wide range of operating conditions, a combined approach utilizing both open- and closed-loop control methods was tested for the first time. Both tests were conducted at flow conditions corresponding to Case 6, shown in Table 2.

4.1 Sub-harmonic Fuel Injection

It is straightforward applying active control using an actuator with higher frequency response than the combustion dynamics. A problem occurs when the maximum frequency response of available actuators is lower than the combustion process one is trying to control. This is often the case in liquid-fuel actuation as many of the commercially available injectors have relatively low frequency response compared to the instability frequencies. To address this problem, a closed-loop sub-harmonic fuel injection approach was attempted in the experiment.

The results are shown in Fig. 7 which displays the pressure oscillation amplitude as a function of the controlled phase delay settings. The control was attempted either with four fuel injectors or two, but the duty cycle was adjusted so that the average fuel flow through the controller remained almost the same in each case. Figure 7b shows that the closed-loop sub-harmonic control approach worked just as effectively. The results are encouraging in that there was no significant drop-off in the performance when compared with the baseline case of Fig. 7a, which used the controlled injection at the fundamental frequency. In both cases, there was more than 10 dB suppression when the phase-delay was controlled properly.

Figure 8 shows an illustration of how the suppression would be achieved despite the fact that sinusoidal functions at harmonic frequencies form an orthogonal set. This approach would work in most cases because the pulsed heat release rarely exhibits a perfect sine wave pattern. For instance, in a typical case, the heat release due to pulsed fuel injection exhibits a periodic modulation at the injection frequency but the shape of the signal is such that it contains additional energy in its higher harmonics. Therefore, the integral over a cycle of the resulting product between pressure and heat release oscillations is not zero but a finite value, which in turn becomes either source or sink term for acoustic energy depending on their relative phase difference.

4.2 Pacemaker-Controller

The pacemaker-controller concept uses two outputs. One set of injectors is driven with an open-loop forcing to reinforce the periodic process, while the other set of injectors is used for controlling the combustion process. In general the open-loop forcing frequency was selected either same as the instability frequency or one of the higher harmonics or sub-harmonic frequencies. Another purpose of this open-loop forcing was to sustain controlled oscillations, which would be needed for providing feedback to the control loop, once the dominant oscillations at the instability frequencies were suppressed. Either a simple phase-delay approach or a proportional time-delay controller was used for setting up the closed control loop.

Figure 9 shows the transfer function response of the pacemaker system covering the range of frequencies from 20 to 200 Hz. Except around the resonant frequencies, where the data become meaningless, the transfer function behaves nearly flat across much of the frequencies. Figure 10 shows the effect of adding a closed-loop controller to this system. As before, the instability amplitude was effectively suppressed with the closed-loop control, and the sub-harmonic injection worked just as effectively in this combination controller.

The last controller utilized a proportional time-delay control strategy. The triggering amplitude was set up so that the duration of the closed-loop pulsed injection was dependant on the instability amplitude. As the instability amplitude grew, the duty cycle of fuel injection increased. The pacemaker-controller concept using the proportional time-delay controller was shown in Fig. 2c. Figure11 shows a long time history of the controlled pressure oscillations when this approach was used in a marginally unstable case. The data shows that the closed-loop actuator stopped injecting fuel when the oscillation amplitude was pushed below a certain level at time t near 0.6 sec. Because the stability is at most marginal at the chosen operating condition, pressure oscillations can grow unexpectedly at any instant. The closed-loop controller turns on when the instantaneous pressure oscillation amplitude exceeds a certain limit which is preset. Onset of such unstable oscillations was suppressed effectively using this approach as shown at time t around 2 sec.

4.3 Flammability Limit Extension

When an active combustion control technique is properly applied, it can not only suppress unwanted oscillations but it can also extend the flammability limit. Figure 12 shows the data that were obtained with a pacemaker-controller combination described in the previous section. While this particular controller was not able to suppress fully-blown high-amplitude instabilities in the middle of the unstable zone, it was able to control moderate-amplitude instabilities near the edge of the unstable zone. Consequently, the unstable zone became narrower as the stable zone was expanded. Also, the lean flammability limit was extended much beyond the typical blow-off limit of the premixed flames, which occurs around the equivalence ratio of 0.5.

The data in Fig. 12 were obtained first by reducing the amount of fuel flux while holding the air flux constant. Without the proper active control in place, the combustor was unstable when operated within the shaded zone. The flame blowout was observed when the equivalence ratio was lowered below the dotted line. By actively controlling the fuel injection scheduling, the unstable zone was reduced as shown by the solid gray lines. Furthermore, the lean flame blow-off limit was significantly extended to equivalence ratio just below 0.2 (dark line). The flame was stable in this experiment, even with the minimum amount of controller fuel flux. The air flux had to be increased to finally obtain the flame blowout.

5. Summary and Concluding Remarks

This paper summarized a joint experimental study between the Naval Air Warfare Center and the University of Maryland to better understand the practical issues related to liquid-fueled active combustion control applied to a model ramjet dump combustor. The first part of the study concentrated on understanding the important physical mechanisms involving liquid-fueled instability suppression and scaling laws, while the focus of the second part study was on building the scientific basis for developing a practical controller. It was shown that transient vortex-droplet interaction, which depends on fuel injection scheduling, could be used to effectively control the spatial and temporal distributions of fuel. This mechanism was utilized in a practical manner to apply an active instability suppression technique.

Some of the important findings and observations in the present study are the following:

1) It was shown that there exists a critical fuel flux which is required to obtain active instability suppression. While the critical fuel flux depends on the manner at which the controller fuel is introduced into the combustion zone, it is very sensitive to the initial amplitude of the instability as well as the fuel droplet size.

2) The droplet size dependency was analytically studied and was compared to the experimental data in the present study. For a given fuel type, the critical fuel flux increased with the fuel droplet size by an exponential factor of 1.4. This relation was derived for a moderate droplet Reynolds number considered in the present study.

3) Novel controller concepts were experimentally tested and were shown to work effectively. One concept was based on using a closed-loop fuel injection at sub-harmonic frequencies. The performance was similar to that using the injection at the instability frequency. In the future this fact could be used to relax the requirements on actuators. Another concept used a combination approach bringing an open- and closed-loop controls simultaneously. The latter approach would be useful when there is a significant drift in the natural instability frequency.

The present study has shown that active combustion control can be a practical technology that enables higher performance in dump combustors. Furthermore, it was demonstrated that the present control technique not only suppressed combustion instabilities but it could also be used to extend the lean flammability limit. While the influence of fuel droplet size on controller effectiveness was demonstrated in the present study, other scaling aspects warrants more detailed future investigation. For instance, the present experimental data showed that the instability amplitude increased with the combustor output scale. Thus, a collaborative study is in progress which considers the effects of inlet flow temperature, combustor Damköhler number, as well as the relative intensity of the combustion.

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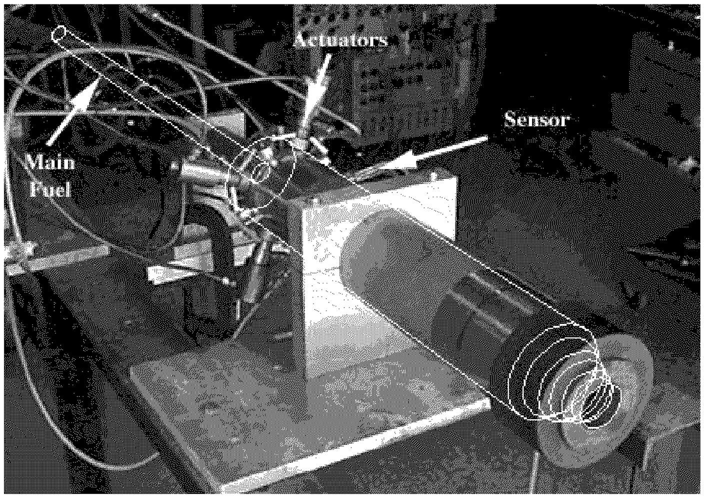


Fig. 1 Actively controlled dump combustor set-up.

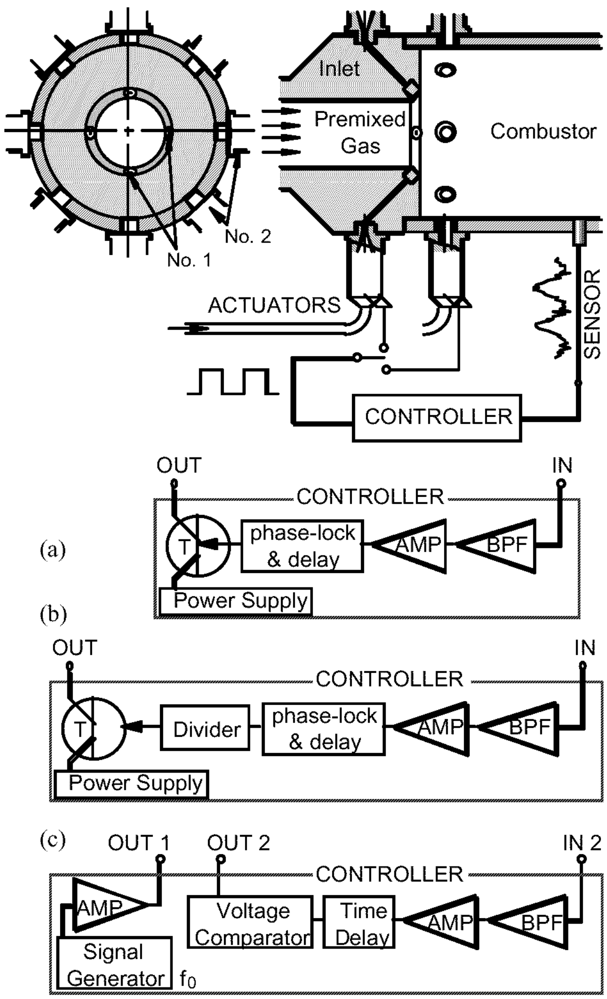
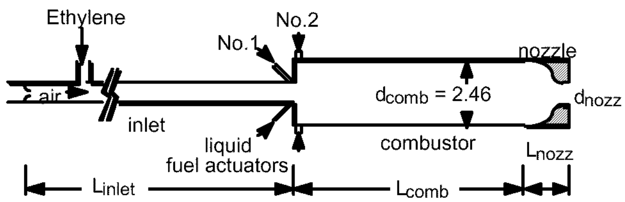


Fig. 2 Active control system. (a) a simple phase-delay circuit, (b) a sub-harmonic fuel injection control circuit, and (c) a pacemaker-controller design.

Table 1 Dump combustor setup for the corresponding cases.



all dimensions are in terms of d_{inlet} = 42 mm

Case	Liquid Fuel	actuator	L_{inlet}	L_{comb}	d_{nozz}	L_{nozz}
1	Ethanol	No. 1	58.5	10.2	1.29	1.85
2	Heptane	No. 1	25.8	12.4	0.615	1.85
3	Heptane	No. 1	25.8	12.9	0.862	1.32
4	Heptane	No. 1	25.8	8.9	0.615	1.85
5	JP-10	No. 2	20.2	15.4	1.36	1.81
6	JP-10	No. 1	20.2	15.4	0.615	1.85

Table 2 Average flow conditions and characteristic parameters for test cases.

Case	Flow Rate (g/sec)					Flow Characteristics			Unstable Conditions			Fuel Droplet			Control Efficiency
	Air	Ethylene	Ethanol	Heptane	JP-10	Power Output (kW)	Re	ϕ	$\frac{\overline{p}_{comb}}{p_{exit}}$	f(Hz)	$\frac{p'_{rms}}{\overline{p}_{comb}}$	D_{32}	Re_f	Stokes	$\frac{(kW)_{pulsed}}{(kW)_{total}}$
1A	45	1.0	0.75	-	-	66	$7.7\ 10^{4}$	0.47	1.02	34	0.008	50	90	0.21	0.30
1B	45	1.3	0.75	-	-	82	$7.7\ 10^{4}$	0.58		35	0.005	50	90	0.21	0.25
2	120	3.3	-	0.62	-	180	$2.0\ 10^{5}$	0.51	2.20	87	0.042	39	180	0.28	0.15
3A	150	5.1	-	0.73	-	270	$2.5\ 10^{5}$	0.59	1.59	98	0.092	36	210	0.27	0.12
3B	200	7.0	-	0.65	-	360	$3.4\ 10^{5}$	0.57	2.06	96	0.089	38	300	0.30	0.08
4	120	3.3	-	0.63	-	180	$2.0\ 10^{5}$	0.51	2.17	95	0.054	39	180	0.31	0.15
5A	270	11	-	-	2.2	630	$4.4\ 10^{5}$	0.72	1.39	120	0.076	10	100	0.034	0.15
5B	270	11	-	-	1.1	580	$4.4\ 10^{5}$	0.69	1.38	120	0.11	10	100	0.034	0.079
5C	270	11	-	-	0.55	560	$4.4\ 10^{5}$	0.66	1.33	122	0.095	10	100	0.034	0.041
5D	610	25	-	-	2.2	1280	$1.0\ 10^{6}$	0.66	2.67	125	0.13	10	240	0.035	0.072
5E	610	25	-	-	1.1	1230	$1.0\ 10^{6}$	0.63	2.72	125	0.21	10	240	0.035	0.037
5F	610	25	-	-	0.55	1210	$1.0\ 10^{6}$	0.62	2.56	125	0.18	10	240	0.035	0.019
6	28	0.48	-	-	0.89	61	$4.7\ 10^{4}$	0.70	1.07	99	0.019	50	45	0.45	0.62

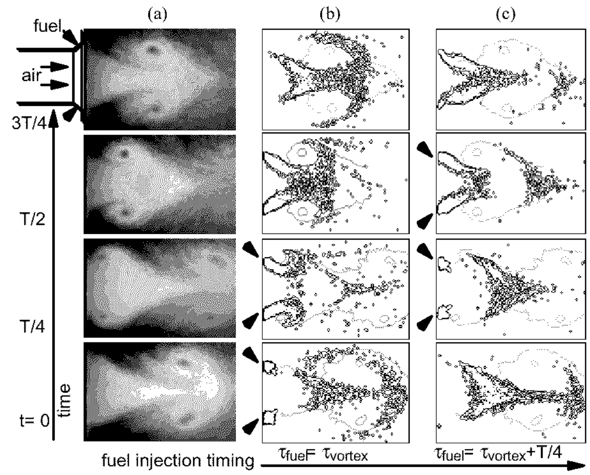


Fig. 3 Fuel dispersion control using timing-dependent vortex-droplet interaction. (a) Underlying flow structure, (b) vortex-synchronized fuel injection, and (c) injection after the vortex shedding

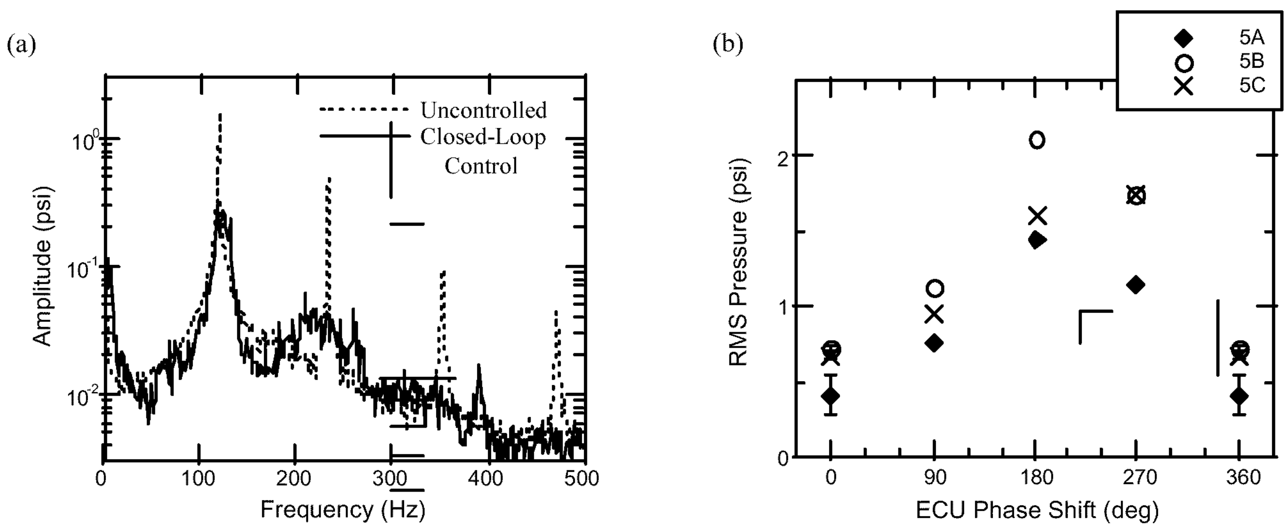


Figure 4. Effect of closed-loop control on pressure oscillation amplitude. (a) Combustor pressure spectra for Case 5A, and (b) pressure oscillation amplitude .vs. relative phase angle.

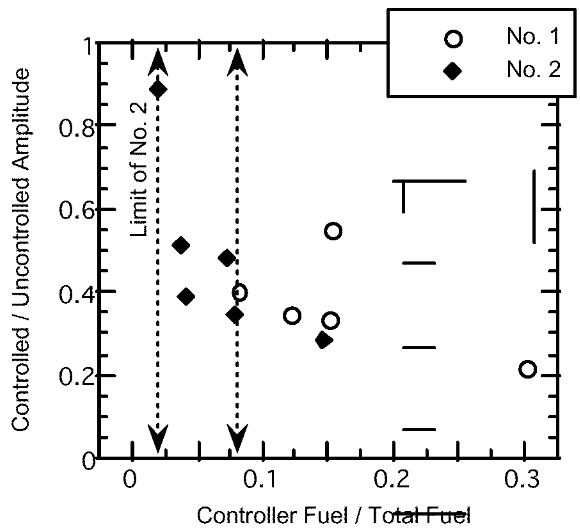


Figure 5. Critical fuel flux for active instability suppression using each actuator system.

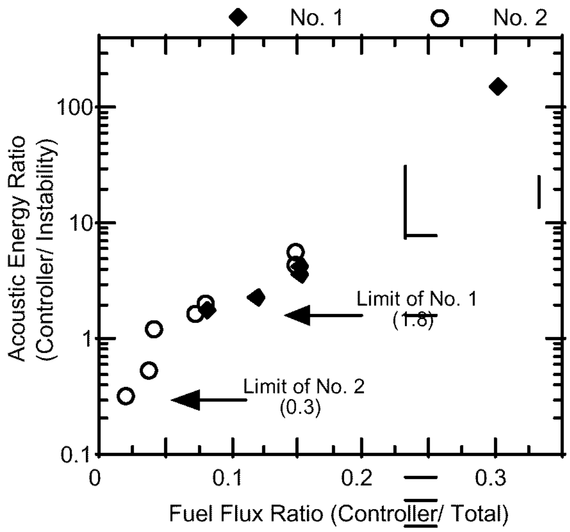


Fig. 6 Comparison of normalized acoustic energy provided by the two actuators.

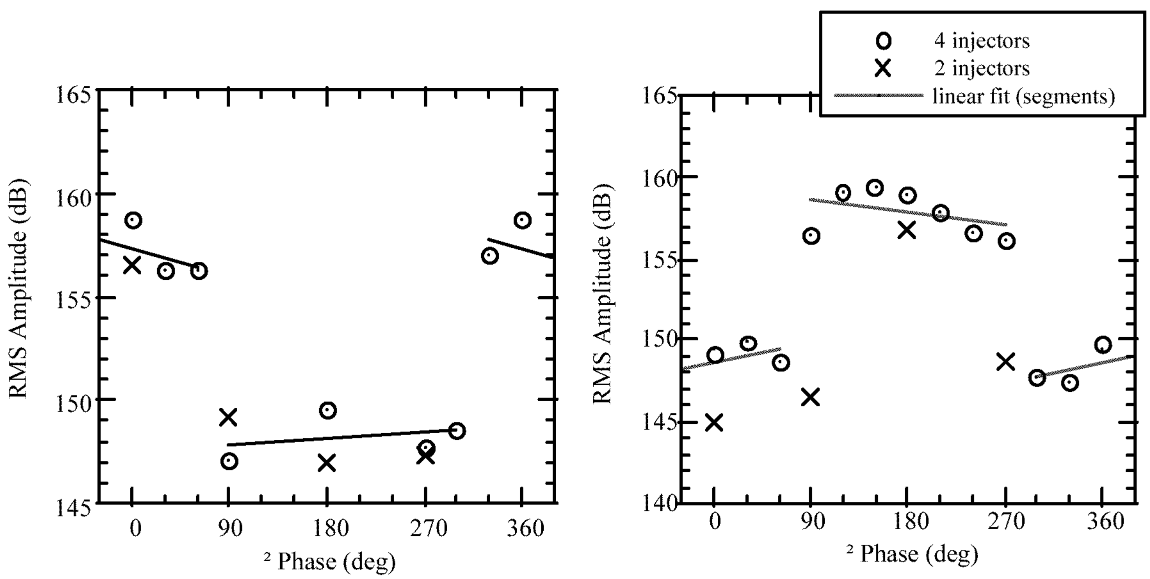


Figure 7. Amplitude of actively suppressed pressure oscillations as a function of controller electronic phase-delay. The plots show the performance of (a) baseline controller using actuation at the instability frequency, and (b) the new controller using actuation at the first sub-harmonic frequency of the instability.

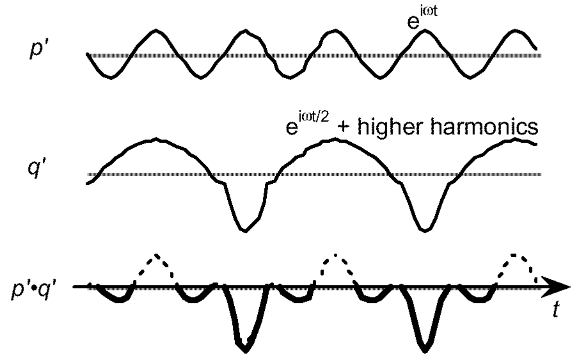


Figure 8. Illustration of acoustic energy reduction even when the actuation frequency is a sub-harmonic of the instability p'.

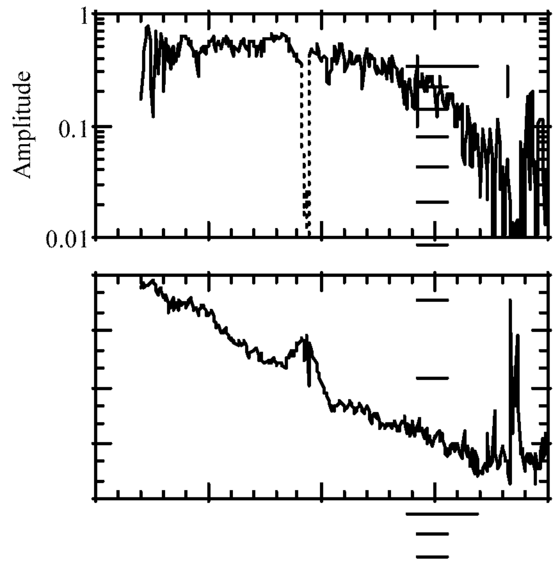


Fig. 9 Transfer function of the pacemaker in the absence of the controller. (a) Amplitude, and (b) phase with respect to the pacemaker frequency.

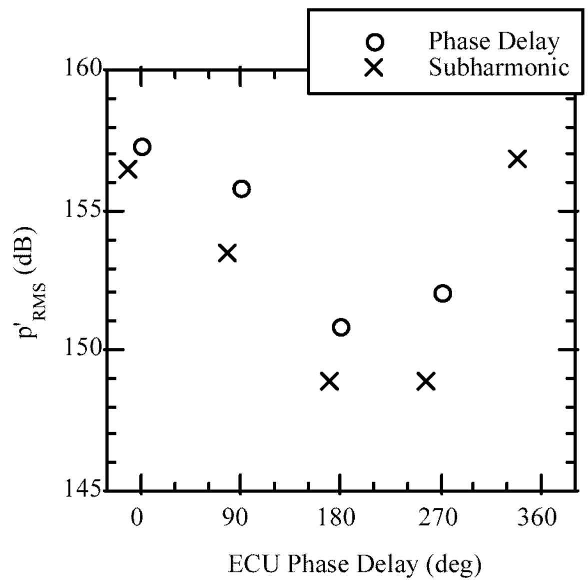


Fig. 10 Demonstration of Pacemaker-Controller in suppressing the instability amplitude.

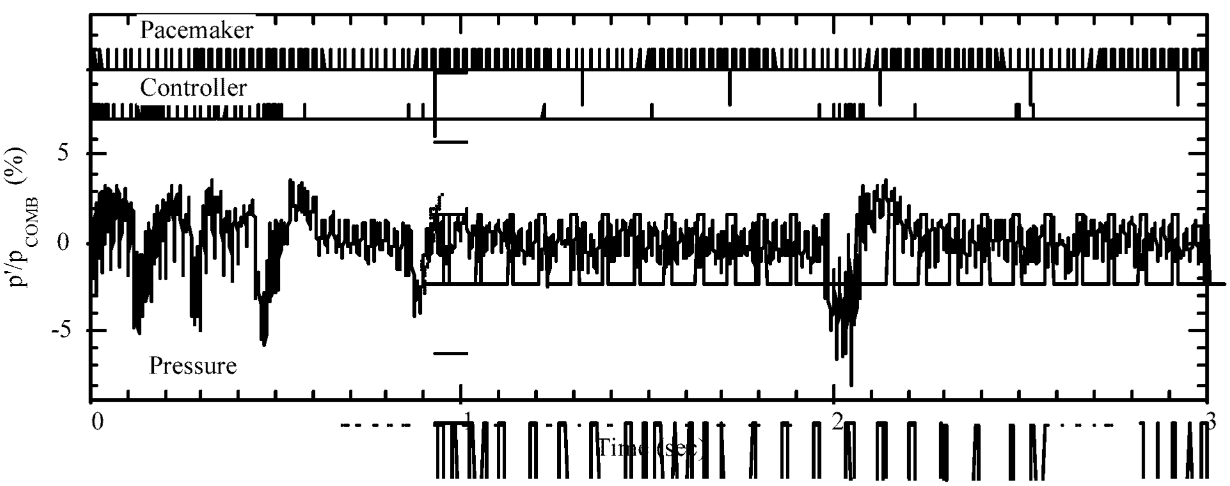


Fig. 11 Instability suppression using a novel Pacemaker-Controller, based on time-delay proportional control design.

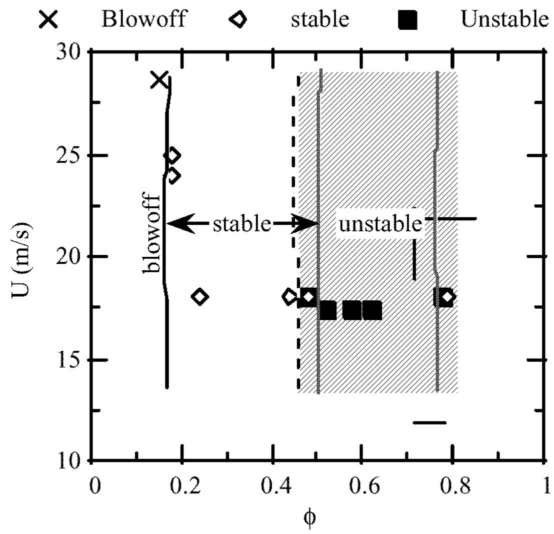


Fig. 12 Flammability map showing the extension of stable combustion limit when a pacemaker-controller was applied.

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Question (F. E. C. Culick, USA)

Towards the end of your paper (Fig 11), you showed that while under control, your system exhibited intermittent instability. Why?

Reply

For demonstration of the "Pacemaker-Controller" concept, we chose an operating condition at which the combustor exhibited two states of dynamic behavior – one with low-amplitude oscillations at less than 1% RMS amplitude, and the other with a much greater amplitude. While this condition was similar to the "hysteresis" behavior that Culick described a few years ago, the state of low-amplitude oscillations was only temporary in our case. As a result, the system, if left uncontrolled, would eventually return to high-amplitude oscillations in time. Our approach of control was to intervene with the closed-loop "controller" only during the onset of instability, quickly brining the oscillations amplitude under control. This approach effectively extend the range of stable operating into the marginally unstable regime.

As a side note, the "Pacemaker", on the other hand, was always on. While its main role was to extend the lean blow-out limit at lower equivalence-ratio conditions, the Pacemaker would also contribute at this operating condition by making the instability behavior more predictable.

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