Closed-Loop Control in a Flame and a Dump Combustor

E. Gutmark, T. P. Parr, K. J. Wilson, D. M. Hanson-Parr, and K. C. Schadow

A closed-loop control system was constructed to control the lift-off height of a premixed flame at the lean flammability limit. Control authority was obtained by forcing the initial shear layer of the fuel/air mixture, thus generating small scale vortices which improved the flame stability. The optimal forcing was determined in open-loop control tests, which defined the effective range and related it to the Kelvin-Helmholz instability of the shear layer. An amplitude modulation (AM) controller was developed using the open-loop frequency as a carrier signal. Bode and Nyquist analyses showed that the flame is stable only in a limited range due to convective time lag, related to the convection time of the vortices. In spite of the high noise level of this turbulent combustion system, it was possible to use linear control theory to analyze the time-averaged transfer functions. The application of lead and lag compensations was studied to extend the stability margins. The control system response to changes in operating conditions such as set-point and flow rates were compared to the open-loop control operation and found to be superior, leading to a small extension of the lean flammability limit relative to an open-loop controller.

The same actuation technique investigated in the flame experiments in conjunction with a different control strategy, are used for active combustion control in the dump combustor. Shear-layer excitation was investigated using acoustic drivers. Parameters affecting the efficiency of the various methods for active combustion control were studied, including frequency, amplitude, and phase information. The effectiveness of the acoustic shear-layer excitation on the combustion characteristics was evaluated. A certain attenuation of the unstable combustion oscillations was obtained with the high frequency acoustic excitation.

Closed-Loop Feedback for Combustion Control

In certain combustor designs with adverse operational conditions (for example, low chamber pressure), combustion is initiated at a certain stand-off distance from the dump or flameholder. The delay of the onset of combustion is due to the presence of large-scale vortical structures in the shear flow and may result in high amplitude pressure oscillations, low combustion efficiency, and narrow flammability margins.

Passive and active control methods, aimed to modify the flow pattern and reduce the coherence of the vortices, were applied to premixed and diffusion flames with valuable results that stabilized the flame and changed the regions of the chemical reaction [1], [2]. These changes obtained by open-loop control were also observed in closed-loop feedback systems for combustion control [3], [4].

A closed-loop active combustion control system requires some feedback signal between the combustion output and the actuators which control the air and fuel flows. Several investigators studied control methods for the suppression of combustion oscillations. Pressure oscillations [5], [6] or light emission fluctuations [3], [7], [8] have been detected by microphones or photodiodes, suitably filtered, delayed, and amplified, and fed back to different types of actuators. The use of radiation to monitor the combustion process was described originally in [9] and [10].

Loudspeakers were used to impose secondary sound waves into the combustor [3], [5], [6], [8]; an oscillating inlet nozzle was studied to stabilize the premixed flame, and tests which were aimed to study the effectiveness of a phase-shift acoustical active control system in a relatively high power combustor of 1 MW with a turbulent inlet flow.

Experimental Arrangement

Flame System

A propane/air premixed circular flame was studied [1]. The air was supplied through a 290 mm long circular pipe with a 19 mm diameter circular orifice exit. The air flow rate varied in the tests from 20 to 100 l/min, yielding exit velocities of 1.65 to 10 m/s. The corresponding Reynolds number range was 2100 to 12000, based on the exit diameter, exit air velocity, and the kinematic viscosity of air at room temperature. The initial velocity RMS was 2%. The propane flow rate was 1.9 l/min.

A schematic description of the control system is given in Fig. 1. The controlled plant consists of three subsystems: acoustics, flow dynamics, and combustion. All the subsystems have links and are interdependent. The output of the plant, i.e., flame standoff, is monitored by sensors and is being fed back and compared with the set-point conditions and subsequently are used as inputs to generate the necessary commands by the controller.

The sensing element in the present system, which is a photodiode, integrates the image of the flame over a predetermined active area to determine the flame location. The

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photodiode voltage is proportional to the flame lift-off height (i.e., the voltage decreases proportionally to the increased lift-off height). This signal is then compared with the desired height, which is determined by the set point bias. The difference between the two signals is used to modulate the amplitude of the carrier frequency. This frequency is the one determined from open-loop tests and linear stability theory of shear layers to be the most effective in suppressing large-scale vortices and stabilizing the flame. The modulated frequency drives the speaker in the flame cavity via an audio amplifier. The speaker is used as the actuator which controls the flame lift-off distance via changes in the flow structure. The control objective is to maintain the flame lift-off height at a predetermined level. Acoustic modulation at the initial instability frequency of the air/fuel mixture was shown to be capable of varying the lift-off height. The present control system changes the amplitude of the carrier frequency such that a desired flame height is maintained.

**Dump Combustor System**

The schematic of the combustor is shown in Fig. 2. Air is supplied into the combustor through a \( D = 6.35 \) cm diameter circular pipe with a flow straightener upstream of the dump plane (sudden expansion). The pipe expands through an angle of \( 7^\circ \) to inject the air through an orifice plate of diameter \( 6.35 \) cm into the combustion chamber. The ethylene fuel is injected through four slots in the orifice plate normal to the air flow. Acoustic modulations are superimposed on the fuel stream by four acoustic drivers. Ethylene is injected at a rate of 0.016 to 0.023 lb/s into 0.255 to 0.484 lb/s air flow, resulting in an equivalence ratio \( \phi \) in the range of 0.71 to 1. The chamber temperature is 1400 to 1800 K at ambient pressure.

The steel combustion chamber is circular with a diameter of 2 \( D \) and length of 8.4 \( D \). The diameter of the exhaust nozzle is 1.65 \( D \).

A block diagram of the closed-loop control system is given in Fig. 2. High frequency response pressure transducers, installed near the dump plane (sudden expansion) and near the exhaust nozzle, are used as sensors to monitor the combustion process. Their signals are fed through an amplifier into a band-pass filter which is centered around the most unstable frequency of the combustion pressure oscillations. The filtered signal is used to phase-lock and phase-shift a sinusoidal signal which is fed into four acoustic drivers via audio amplifiers. The acoustic drivers excite acoustic resonance in the connecting tube which modulate the fuel jet and the shear layer at the inlet to the combustion chamber. The shear layer and fuel modulations change the mixing pattern between the air jet and the fuel, and thus can vary the heat release rate.

The dump combustor control system is designed to suppress pressure oscillations in the combustion chamber. These oscillations are excited naturally when the interaction between flow instabilities and the combustion chamber acoustics provide conditions in which pressure oscillations are in phase with the heat release fluctuations (Rayleigh criterion).

**Results and Discussion**

**Transfer Functions (System Stability)**

Stability analysis of the system was done using the Bode method. The carrier frequency was modulated with bandwidth limited noise and the corresponding response of the sensor was measured. The resulting Bode plot is shown in Fig. 3. The Bode plot is a result of a long time average (209 s). The system is highly turbulent with high random noise level, yielding a coherence level between the driving signal and the height detector, which was typically lower than 0.3. Short average Bode plots were extremely noisy, with an RMS fluctuation of about 90° in angle and about 6 dB in magnitude, rendering any analysis impossible. However, they show that due to noise the system can occasionally exceed a gain of unity when the phase shift is over 180°, resulting in an unstable controller operation. The quasi
linear drop of the phase angle with frequency indicates a time lag in the system. The 180° phase shift occurs over a frequency range of about 18 Hz, which translates to a time lag of 28 ms. Physically, this time lag relates to the convective velocity of the combustible mixture. The acoustic time delay inside the cavity is only of the order of 1 ms. However, when the flame is lifted, the convection time of the vortices from the nozzle to the flame is of the order of 28 ms. To obtain wide stability margins, the gain of the system has to fall below zero decibels before the phase acquires a shift of 180°. In the present system, the gain falls relatively slowly, and considering the noise fluctuations, it still has a positive gain at the phase cross-over point (Fig. 3). This yields a marginally stable system. The spectrum of the CH/C\textsubscript{2} emission signal shows a hump at a frequency of 18 Hz, corresponding to the phase cross-over point. This ability to predict the behavior of the system using linear control theory, in spite of its high noise level, is one of the interesting outcomes of the present work.

The need to reduce the gain at high frequencies, to avoid positive gain at phase shift angles higher than 180°, and the general requirement to reduce high frequency noise, suggest the use of a low-pass filter, which was incorporated in the present system. The improvement of the signal to noise was clear from the coherence plot which showed a significant increase up to 0.7. However, the rapid roll-off of the gain at a frequency of 16 Hz is concurrent with an increase in the phase lag, such that 180° cross-over moves to 8 Hz. For this condition, the flame becomes highly unstable, detaching and reattaching to the flameholder at a nearly steady frequency of 8 Hz.

Response to Changes in Operating Conditions

The mechanism of controlling the lift-off height is explained here. Previous experiments [1],[2] showed that the flame lift-off phenomenon is related to the existence of large-scale vortices in the air/fuel mixture flow near the nozzle. The large strain rates induced by the vortex roll-up process result in local extinction and the transition of the flame stabilization location to a downstream point. The roll-up pattern of the flow can be altered by acoustically forcing at a frequency which is sufficiently larger than the dominant vortex frequency. This excitation forces the flow to form smaller-scale vortices which in turn shifts the flame stabilization point upstream closer to the nozzle exit. In the present experiment, the flame stand-off distance is monitored by a photodiode and controlled by acoustic drivers. When the flame is higher than desired, the photodiode voltage is less than the set point. The error signal results in increased amplitude of the driving frequency which forces the flame to reduce the lift-off height. When the flame is lower than the set-point, the photodiode voltage is too high, leading to a reduction in the amplitude of the driving frequency and a subsequent increase in the flame lift-off height. The two cases are not symmetric and the difference in the physical system response is discussed in this section. The response of the closed-loop control system to changes in operating conditions was tested by a step change in the set point and in the mixture flow rate.

The step change in the height set-point was first obtained for an open-loop system. The step change in the height set point is manifested in the speaker’s driving signal as a sudden change in the modulation amplitude and in the height detector signal as a change in its level. The time response of the flame to the reduction in the forcing amplitude is about 2 ms while the response to the increase in amplitude is 15 ms. This difference is another manifestation of the convective time delay; the first change occurs when the flame is located near the flameholder, while for the second one the flame is lifted to a larger distance. Another interesting observation is the difference between the rate of change in the two cases. When the flame moves from the low height to the higher, the response rate is only slightly over 1/2 the rate for the reverse motion. The difference is related to the fact that the motion upstream is caused actively by increasing the forcing level, while for the downstream motion the forcing releases the flame to propagate downstream by itself.

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Closed-loop control of the pressure oscillations in the dump combustor was employed by varying the phase of the acoustic driving signal relative to the pressure fluctuations measured 1 inch downstream of the dump plane. The speakers were driven in a range of $\psi = 40^\circ$ to $400^\circ$ phase shift angles relative to the pressure signal. The variation of the peak amplitude of the instability frequency as a function of the phase shift angle is shown in Fig. 5. A reduction of 47% in the peak amplitude relative to the uncontrolled combustion was obtained at $\psi = 40^\circ$. The horizontal dashed line on the graph represents the amplitude of the uncontrolled combustion. In a range of phase shift angles between $\psi = 170^\circ$ to $350^\circ$, the amplitude of oscillations was increased relative to the unforced combustion, with a peak increase of 50% relative to the unforced conditions at $\psi = 300^\circ$.

Concurrent with the changes of amplitude, there is a cyclic variation of the instability frequency. A minimum frequency of 280 Hz was measured at the highest suppression phase angle, while $f = 310$ Hz at the point of maximum amplitude. This frequency change did not have a considerable effect on the close-loop performance since the variation range was small relative to the window width of the band-pass filter.

**Effect of Control on the Flammability Limit**

The effect of control on the lean flammability limit was studied at two phase shift angles: one corresponding to effective suppression conditions and one at which the instability is augmented. RMS of the pressure oscillations in the combustion chamber were measured as the equivalence ratio (fuel to air ratio) was varied (Fig. 6). The instability of the uncontrolled combustion became highly amplified at $\phi = 0.93$. The amplitude of the fluctuations increased and the frequency dropped to near 200 Hz. The high level oscillations continued until the lean flammability limit (extinguished combustion) was reached at $\phi = 0.72$. When the flame was controlled at a phase shift angle of $\psi = 80^\circ$ corresponding to a maximum suppression of the pressure oscillations, the onset of high amplitude instability was delayed to $\phi = 0.81$ and was blown out only at $\phi = 0.54$. The onset of large amplitude pressure oscillations was delayed (to $\phi = 0.87$) also with a phase shift angle of $320^\circ$ corresponding to augmentation of the instability, but the flammability limit shifted to a higher $\phi$ of 0.78.
Control of the Dump Combustor at High Air Flow Rate

As the air flow rate increases, the pattern of instability becomes bi-modal and therefore more difficult to control. The unstable frequencies are 310 Hz and 360 Hz. During a cycle of phase shift in the control measurements the amplitudes of the two peaks change and they become alternately dominant.

Due to this bi-modal spectrum, the window of the band-pass filter was widened to include the two frequencies. However, the switching of the dominant frequencies complicates the locking of the driving signal and causes shifts in the relative phase due to the variation of the phase caused by the band pass filter when operating off the center frequency. The amplitude of the 310 Hz oscillations shows cyclic response to the forcing, with minimum values at 300° and a maximum at 180°. The reduction at 310° is more than 35% relative to the unforced amplitude. The higher frequency of 360 Hz showed lower variations relative to the unforced level with a minimum at 180° and a maximum at 360°. The maximum reduction of amplitude was only 20%.

The effect of control on the lean flammability limit was tested also for the high flow rate. The unforced combustion was compared with a controlled condition at a phase shift of \( \psi = 340° \). The effect was very minor with a slight increase of the equivalence ratio which corresponds to the onset of high-level instability, from \( \phi = 0.78 \) to 0.81.

Flame Control

The premixed flame exhibits a turbulent nature at the lean flammability limit especially for high fuel flow rates, which require high air flow rate and high Reynolds number at this condition. Analysis of the dynamic frequency-response of the system showed a highly nonlinear system with large noise level. The nonlinearity of the system is primarily related to nonlinearity in the shear layer such as vortex roll-up and merging. The nonlinearity of the system was bypassed by introducing the amplitude-modulation (AM) control scheme. Open-loop control tests and linear stability theory of shear layers were used to select an effective single frequency for the control signal. By forcing the shear layer at this most amplified frequency, the merging process is suppressed such that the mechanism for generating vortices at the subharmonic frequencies is eliminated. The forcing is also supplying effectively the required control authority, as demonstrated in open-loop control tests. The response of the lifted flame to this forcing is linear in a certain range, i.e., increased amplitude yields a corresponding linear reduction of the lift-off distance. The linear behavior is restricted at the two extremes: on the lower side by the flameholder and at the downstream side by the blow-out limit.

The AM controller did not solve the noise problem; however, surprisingly, the information of long time-averaged Bode or Nyquist plots was sufficient to obtain a good prediction of the system stability margins based on linear control theory.

The stability margins of the system were limited by a convective time lag inherent to the plant due to the finite time which is required for the vortices to be convected from the flameholder to the flame. Attempts to reduce this problem by adding a lead compensation network have hampered by the fact that the improvements in the phase angle is accompanied by an increase in gain at high frequencies which causes reduced stability margins. The time lag problem is alleviated by operating the flame at the utmost upstream location, thus reducing the convective time and reducing the fluctuations level.

Further improvement of the system is planned by applying nonlinear control at the boundaries utilizing a rate feedback controller outside the linear range.

Dump Combustor Control

Active combustion control was tested in a dump combustor for two air mass flow rates corresponding to 33 and 66 m/s at the inlet. In both low and high air flow rates the fuel modulation suppressed the instability at a certain range of phase shift angles and increased the instability level at other angles. For the low flow rate, a 47% suppression was obtained at a phase angle of 40° while an augmentation of 50% was measured at 300°. The total RMS was reduced by 12% and increased by 8% at the same frequencies, respectively. The reduced oscillations produced also a delayed onset of high level instability oscillations at the lean flammability limit and an extension of this limit from an equivalence ratio of 0.72 to 0.54.

Increasing the amplitude of the acoustic forcing resulted in a higher suppression of the peak amplitude at the effective phase shift angles, which was nearly proportional to the forcing level up to a certain limit of forcing level where leveling off occurred. The total RMS reduction was less affected by the forcing level. High flow rate combustion instability was characterized by a bi-modal spectrum which reduces the effectiveness of the phase-lock control due to the varying dominant frequency. It is required for such operational conditions to widen the window of the band-pass filter which subsequently introduces phase errors due to the dependence of the phase on the frequency when the dominant frequency is off the center frequency of the filter. The effectiveness of the control system is thus reduced, such that the highest suppression was 35%, at a phase shift angle of 300°, while the highest increase was 20% at 180°. At this flow rate the control did not have any effect on the combustion instability and blow-out at the lean flammability limit. In order to control a bi-modal instability, a dual-loop controller is preferred. The two unstable components can be suppressed independently by optimizing the time delay for each one of them. Such system was shown to be more effective in the simultaneous suppression of the two modes and extension of the lean flammability limit.

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